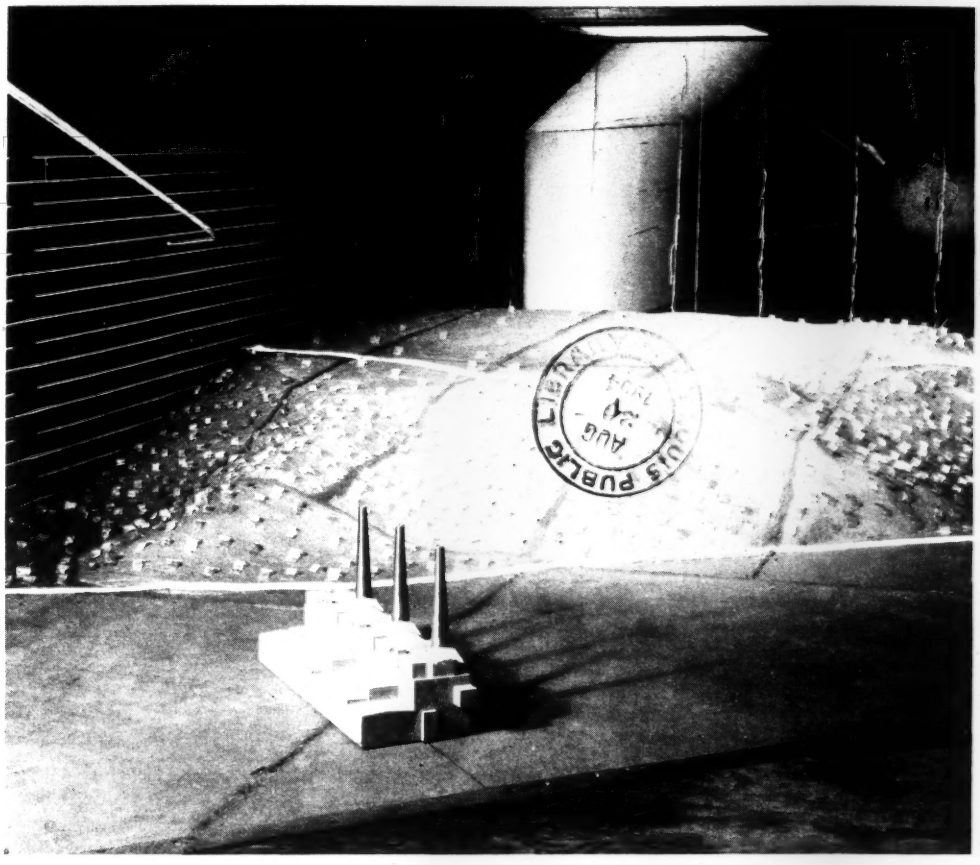
Air Repair



Wind Tunnels Help In Air Pollution Control Studies

(pages 13 and 24)

The Journal of the

AIR POLLUTION CONTROL ASSOCIATION

4400 FIFTH AVENUE **PITTSBURGH 13, PA.**

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Air Repair

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EDITOR'S NOTE—Discussion of papers in May AIR REPAIR can be found on pages 45-52 of this issue. Discussion of "Planning a State-wide Air Pollution Advisory Service" will appear in the November issue. Beginning with this issue, papers will be published with their discussions appended.

The Editor welcomes writers interested in air pollution problems and encourages them to use the pages of this journal for the expression of their opinions. But neither he nor the Association assumes responsibility for the validity of the opinions expressed herein.

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AIR POLLUTION CONTROL ASSOCIATION

4400 FIFTH AVENUE . . . PITTSBURGH 13, PENNSYLVANIA

FELLOW MEMBERS:

AIR REPAIR has achieved national prominence and international recognition, by becoming the first technical publication with its contents devoted entirely to atmospheric pollution problems. It is now universally accepted and is growing in stature in proportion to the rapid growth of our Association. This growth is measured by our ever increasing membership and the continuing service we render to our fellowman.

The Association's objective is to promote the knowledge and practice of Air Pollution Control. The development of reasonable standards and practices is a direct way to promote this objective. In order to obtain these, the Technical Coordinating Committees of the Association are encouraged to carry to a conclusion, work assignments already well started. It will be a major contribution to all, when the completed reports of these Committees are published in AIR REPAIR. Questions pertaining to committee structure and functions should be addressed to the office of the Executive Secretary at Pittsburgh, Pa., by those unfamiliar with the over-all operation of the Association.

We welcome suggestions you may have concerning the services which you feel the Association can render through its Committees. By acknowledging this request, each member can feel he has an active participation in the work of the Association. An example of individual participation is the recent preliminary report of the Air Pollution Measurements Committee. This work was originally initiated through individual suggestions. It is now possible to standardize procedures in this generally used method of measuring one kind of air pollution, allowing results in several locations to be understandingly correlated.

The present goal for each Technical Coordinating Committee is to submit a report before the Detroit meeting in May of 1955. You and I can help by suggesting our needs to the Committees and volunteering our service in this new and challenging endeavor.

Gordon P. Larson

Gordon P. Larson
President

Development of Incinerator For Cleaning Bitumastic Material From Steel Drums

By Milton Reizenstein
Smoke Regulation Engineer
Baltimore, Md.

The barrage of complaints about smoke and soot, from the neighbors of the steel drum cleaning incinerator at the plant of the American Cooperage and Steel Drum Company, was a "headache" for the Division of Smoke Control of the City of Baltimore.

The business of the Cooperage concern is to clean, and otherwise put into condition for resale, steel drums which have been used to contain a wide variety of substances. Not all of the contents of the emptied, used drums are easily removed.

A substance most difficult to remove from the surfaces of the drums is a bitumastic paint or spread of the type used to undercoat the fenders of automobiles which is very sticky, causing much effort and time to be expended in its cleaning. It has been found by the used-steel-drum-trade that the only economical way to reclaim such drums is to burn out the contents and wire brush away the remaining ash. Originally, in order to hasten the burning process, a quantity of an inflammable liquid was poured into the dirty drums and ignited. A profusion of soot and dense black smoke, a terrible nuisance to the neighbors of the drum company as long as the burning endured, justifying complaints, was given off. This method was not a satisfactory way to clean the drums to the company, because it necessitated repeated burning efforts.

Some years ago the company built a furnace in which they would burn about a dozen drums at a time. Smoke and soot were exhausted by natural draft, through a stack connected to the furnace, spreading these undesirable effluents over the plant as well as their neighbors. An induced draft fan between the furnace and the stack was added, but it did not reduce the magnitude of the nuisance; instead, it tended to spread the products of improper combustion over a wider area.

This resulted in forbidding further use of the incinerating furnace and the burning of drums in the open or in any manner which would cause smoke. In spite of this, the drum cleaners would occasionally burn out drums, which were resistant to cleaning by other methods, with a continued super-abundance of smoke and soot. The restriction on burning drums hampered the company in their usual daily operations.

Hampering a business activity is not a policy of our office. Our aim is to be considerate of industry's normal activities, providing the neighbors of an industry are happy, within the limits of our work and authority. Therefore, it was felt necessary to improve this situation.

An article in "Air Repair", the journal of the Air Pollution Control Association, led to checking with other operators. Investigation of existing plants in the Pittsburgh and Brooklyn areas showed that none of them had the real answer to atmospheric cleanliness combined with economy and reliability of equipment, although serious attempts had been made to solve the problem.

In 1952 an improved incinerator unit was completed and put into service. It has six gas burners staggered along each side of the furnace (26 ft. long) throwing their flames toward the opposite wall. The 12 burners have a total capacity of 3000 cfh., using natural gas with 1050 Btu's per cubic foot. Air for the burners is furnished by a single stage blower with a capacity of 51,000 cfh., directly driven by a 3 hp. motor. The flames from 12 proportional mixing natural gas burners impinge upon the outer surfaces of the drums as they proceed, open end down to permit the burning "gunk" to fall out. Removal of the "gunk" from the track rails and the area between and beneath the rails is performed manually. It is done about once a week to prevent its building up and hampering the operation of the machinery.

The furnace has an overall width of 7 ft. and an overall height of 8 ft. The entire incinerator is in an open yard, which means that steam tracers must be used on the water lines in cold weather to prevent freezing and bursting of pipes and hydraulic equipment.

The furnace gases are drawn through a rectangular breeching and a centrifugal wash collector, large enough to satisfactorily remove the smoke and soot from 10,200 cfm., by means of an exhauster fan powered by 15 hp., 1600 rpm. induction motor with V-belt drive. The gases are then blown into the atmosphere, with no visible contaminants, through a short section of stack.

City water forced through a spray nozzle in the wash collector, is used to separate the smoke and particulate matter from the furnace gases. This water is used over and over again by means of a recirculating system. A centrifugal pump of 180 gpm. directly driven by a 5 hp. induction motor performs this task. A motor driven pump of similar size forces cooling water through the portions of the conveyor which are subject to furnace heat. A 1½ hp. motor drives the drum conveyor through a gear train. Residue consisting of particulate matter collected from the furnace gases is removed from a

(Concluded on page 44)

Appraisal of Odor Problems

By Amos Turk, Ph.D.
Tarrywile Lake Road, Danbury, Conn.

In practical problems involving the abatement of odor nuisances, some or all of the following questions will arise:

1. What is the source of the odor?
2. What is the predicted effectiveness of each of the various abatement alternatives?
3. What is the predicted capital equipment cost?
4. What is the predicted maintenance cost?
5. After adoption of the odor abatement method, what is its actual effectiveness?

These questions are not listed as all-inclusive of the odor problems arising in air pollution; they are instead those questions whose appraisal can be helped by methods of chemical and organoleptic analysis. Questions of other types, such as "will the pressure be off after the election?" or "what were abatement costs last year?" are political or actuarial, not analytical.

It is thus the purpose of this paper to review the role of analytical methods in the appraisal of odor problems in air pollution.

Analysis in Tracing Odors to Source

In many cases, the source of an offensive odor is all too obvious, and requires no analysis for its confirmation. Circumstances will arise, however, where the source is a matter of dispute and must be traced or objectively verified. Especially where city — or area-wide pollution studies are being made, the problem of source will be complex and will require careful methods for sampling and analysis.

Sampling

The fact that practically all "odorous" atmospheres contain absolute contaminations in the range below 1 ppm. (by volume) makes it almost valueless to collect samples without concentrating them. The three important methods for sampling odorous atmospheres and simultaneously concentrating their components are (a) adsorption, (b) absorbtion, and (c) condensation. In all cases, standard precautions for obtaining representative samples must be exercised: for odorant sampling these include prefiltering for particulate matter, accurate metering, and avoiding recycling of sampled air.

Sampling by Adsorption — Any gas or vapor will, to some degree, adhere to any solid surface at ordinary or low temperatures. This phenomenon is called adsorption. Porous solids expose not only their exterior surface, but their interior surfaces as well, and some such solids indeed possess a vast network of extremely minute channels and sub-microscopic pores within their body. Such materials have practical value as adsorbents. These solids include activated carbon, silica gel, activated alumina, and various active earths. All these differ widely in the number and kinds of substances they adsorb, as well as in the amount of sorbed substances they will retain.

In general, the siliceous, metallic oxide and active earth types of adsorbents are electrically polar — that is, their molecular structure contains an unsymmetrical electron distribution. Since polar substances have strong attraction for one another and since water is highly polar, polar adsorbents retain atmospheric moisture. Siliceous adsorbents, usually silica gel or activated alumina, may advantageously be used for short duration sampling from atmospheres which contain sufficiently high concentrations of gases or vapors to be collected or which are sufficiently dry so that the adsorbent does not become moisture saturated before the sampling is complete. When sampling for odorants is involved, such circumstances are not usually realized and polar sorbents are inapplicable.

Activated carbon, which is electrically non-polar, is capable of adsorbing organic gases and vapors in preference to atmospheric moisture and is, consequently, the preferred adsorbent for odorant sampling. In fact, activated carbon with previously adsorbed moisture will lose such moisture by displacement by organic gases and vapors from odorous atmospheres. Such displacement of moisture is not exhibited to any significant extent by siliceous adsorbents.

The efficiency of adsorption of vapors by activated carbon is higher for materials of higher molecular weight,— for materials with boiling points above O°C., adsorption efficiency is sufficiently high so that fairly thin beds (about one inch) of granular material are sufficient for complete adsorption at moderate flow rates. Most organic odorants fall into this classification, so that activated carbon becomes generally applicable for this sampling. For some few specific exceptions, such as hydrogen sulfide, sampling by absorption (see below) may be preferable. Data on specifications of carbon sorbents and on retentivities of carbon for various odorous vapors have been published elsewhere[11].

Adsorbed gases and vapors may be desorbed from activated carbon by (a) displacement of the adsorbed material by superheated steam and (b) heating the carbon under vacuum and distilling the desorbed material into cold traps.

For steam displacement, the saturated carbon is flushed with super-heated steam at 300°C. or higher. The effluent steam and displaced vapors are condensed and held for analysis. Flushing is continued until the condensate is substantially odorless.

For vacuum desorption, the saturated carbon is connected to a train of three traps in series, which are im-

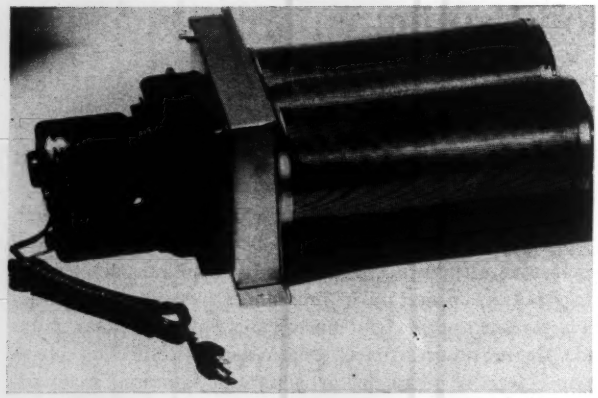

Fig. 1. Activated Carbon Sampling Unit.

mersed in ice-salt, dry ice and liquid nitrogen, respectively. The entire system is evacuated and pumping is continued at a pressure of about one micron of Hg. until distillation practically ceases. During the pumping, the carbon sample is held at a temperature of 200-250°C.

The odorants will be condensed in the cold traps. To avoid escape of the lightest material, it may be advantageous to place fresh activated carbon in the last (coldest) trap. These light odors may then be regained by warming the carbon.

Figure 1 illustrates a convenient form of activated carbon sampling equipment consisting of two canisters (Figure 2) connected to a 50 cfm. blower.

Sampling by absorption. Specific odorous gases or simple mixtures may sometimes be collected by absorption. When a non-reacting liquid is used, the absorption efficiency is limited by the volume of gas sampled per given volume of absorbent and by the volatility of the gas. Various types of absorbing devices (bubblers, packed towers, spiral absorbers, etc.) have been used and when properly applied will show efficiencies in the vicinity of 90%. This performance can be markedly improved when chemical reaction is used (e.g., neutralization of acids or bases, oxidation[3-6-7] or reduction[12]).

Absorption methods, however, suffer from serious limitations in odor tracing. For non-chemical absorption, the problem of separating odorants from a large quantity of solvent may be formidable.

Direct spectrometric analysis of the solution is sometimes valuable, using double-beam infrared equipment which makes it possible to record directly the difference between the spectrum of the pure solvent and of the solution. For chemical absorption, the essential limitation is the fact that there is no general relation between odor and chemical reactivity, and odor tracing may therefore not be possible.

Condensation

Collection of odorants by condensation at low temperatures has a number of distinct advantages over any other collection method. First, the collected odorous material is immediately available for further separation or analysis, without requiring the removal of solvents or desorption from an adsorbent. Second, condensation is the most reliable method of preserving the odorants without chemical reaction with any part of the collecting device or among themselves. The main disadvantages of collection by condensation are that the equipment is cumbersome and requires rather frequent attention and that large quantities of water are always condensed together with the collected odorants. However, the admixture of atmospheric odorants with water is not too serious a problem because their extraction from it is experimentally simple.

A special problem in low temperature collection technique is caused by the formation of condensation mists when the sampled air is cooled. Such mists are composed of solid or liquid particles of widely varying sizes, and often pass through the cold traps in sufficient proportion to reduce significantly the collection efficiency of the equipment. It is, therefore, necessary to provide a simple filter, such as a glass wool plug, within the cold trap to minimize such losses of particulate matter produced by condensation. As collection proceeds, the solid condensate which forms in the trap acts as a filter and

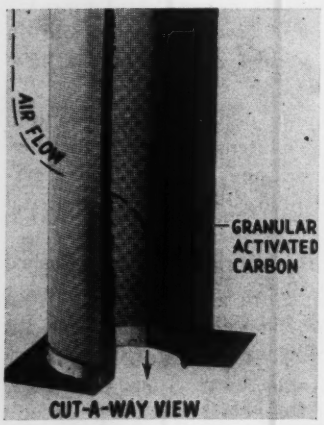

Fig. 2. Activated Carbon Canister.

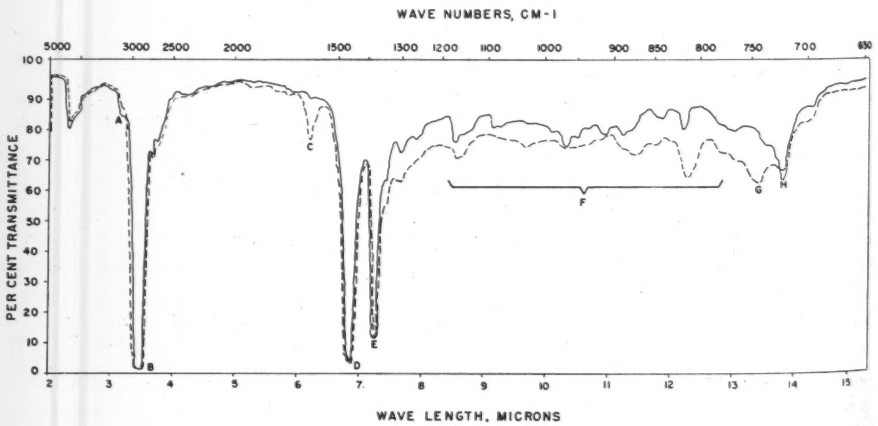

Fig. 4. Comparison of infrared spectra.

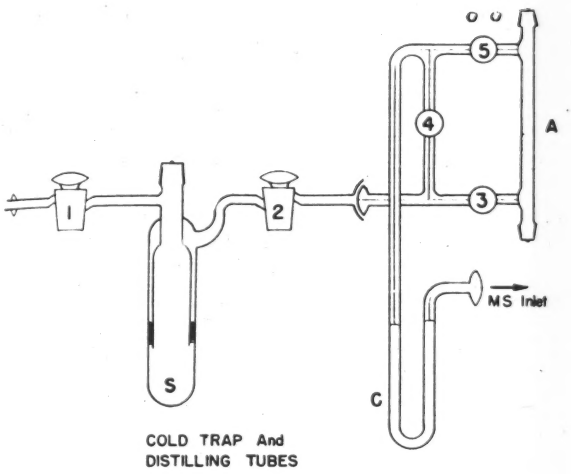

Fig. 3. Condensation Trap.

collection efficiency becomes higher and higher until the resistance of the equipment to air flow becomes prohibitive. Several interesting studies of collection efficiencies by condensation have been reported[2-8].

Refrigerants most commonly used are solid carbon dioxide ("dry ice") baths, and liquid air or oxygen. Liquid nitrogen may condense atmospheric oxygen at low sampling rates and must therefore be used with caution. The fire and explosion hazards of liquid air or oxygen must also be recognized.

A typical condensation trap, as reported by Shepherd[10] is the sampling tube S in Figure 3.

Analysis

Samples collected by any of the methods described above may be analyzed by conventional, spectrometric, chromatographic, or other special methods. Although it is beyond the scope of this paper to elaborate each of these, a number of illustrative examples will be cited.

Los Angeles. Sampling by low-temperature condensation followed by mass spectrometric analysis was used by Shepherd and co-workers[10] to analyze Los Angeles odorants. It was thus possible to identify specific compounds such as acetylene, benzene, toluene, trichloroethylene, sulfur dioxide and other.

Detroit. A problem arose in tracing a particular vapor which was causing premature saturation of an activated carbon system. The oil in the filters preceding the carbon was suspected especially since the filters were being subjected to a warm air flow from a bank of pre-heaters, but proof was lacking. The activated carbon was desorbed with superheated steam, and the condensed oil was washed with concentrated sulfuric acid to remove organic matter other than saturated paraffin hydrocarbons. The comparison of the infrared spectra [13] of this material with that of the filter oil is shown in Figure 4. The lettered points label typical absorption frequencies for A: hydroxyl; B and D: carbon-hydrogen; C: carbon unsaturation, washed out of carbon sorbate with sulfuric acid; E: methyl groups; F: general vibration of molecular skelton; G: aromatic rings (also washed out of carbon sorbate with acid); H: molecular chain end vibration. The solid line represents the filter oil; the dotted line the material adsorbed by the carbon. The source of the vapor is thus definitely traced to the filter oil.

Other examples include the infrared analyses of gaseous pollutants sampled by condensation in Philadelphia[8] and mass and infrared spectra of odorous components of apple and lemon storages[15].

Analysis in Predicting and Measuring the Effectiveness and Costs of Abatement Methods

The appraisal of odor abatement methods or equipment by analysis is far cheaper than by the too-often used device of trial and error. The questions involved will be considered separately for each of the various abatement methods commercially available, namely: counteraction, masking, adsorption, incineration, catalytic combustion and scrubbing.

Counteraction. The objective of odor counteraction methods is to reduce odor intensity of an atmosphere by the admixture of other selected gases or vapors. The evaluation of such abatement methods must therefore involve measurements of odor intensity, necessarily organoleptic. It should be emphasized that the quality of intensity must be kept distinct from other considerations such as odor preference, quality, and threshold value, just as loudness of sound is different from other auditory characteristics.

Many studies concerned with intensity use a subjective scale such as:

0 — no odor
1 — just noticeable odor
2 — definite odor
3 — strong odor
4 — overpowering odor

Scales of this type suffer from the limitations that they are not related to duplicable standards and one would, therefore, expect difficulty in reproducing results from laboratory to laboratory.

Recently Beck[1] at Yale has investigated this problem from the viewpoint of establishing a psychophysical scaling method which is based on a duplicable series of standard odorant intensities. The physical scale used was a series of tubes of heptaldehyde (odorant) dissolved in benzyl benzoate (odorless diluent), arranged in a logarithmic concentration series. Intensity of a given odorant was measured by matching it to a standard odorant solution. In studying alcohols and esters, Beck found that (1) subjects can make quantitative odor intensity matches which are consistent in repeated trials and (2) in broad trends the data of one subject agrees with that of another. This technique therefore provides an objective approach to the independent evaluation of counteraction methods and deserves further attention.

Quantitative odor intensity tests will aid in predict-

ing the amount of counteractant needed for a given application, and hence in predicting operating costs. Capital equipment costs, usually low for this abatement method, will also depend in a simple way on the total quantity of counteractant to be applied.

Masking. The practical objective of masking is to make odors psychologically more acceptable, by the admixture of other odorants. Masking may also be considered as the process of making a given odor unrecognizable by substituting another odor in its place, but such a step is obviously useless if the substitute ordor is equally or more objectionable. Conversely, the process *is* useful if the objectionable character is eliminated, even though some recognition remains. From the air pollution viewpoint, the first definition is much more satisfactory, even though its measurement will be more difficult.

The problem of measuring phychological acceptability has been neatly sidestepped since ancient times with the sentence "De gustibus non est disputandum." However, the method of difference preference tests[4] may be applied to determine whether or not masking has brought about an improvement, and thereby to establish at least a relative criterion for its efficacy. The use of triangle testing (selecting the odd one of three odors) facilitates the statistical measurement of the reliability of such results. One of the most dependable methods for ascertaining odor preferences in an air pollution work is the population survey.

A few remarks should be added about the special problems of organoleptic testing in air pollution work. The experimental situation is entirely different from that of perfume, food, or other product testing, where the odor can be brought to or removed from the subject at will. In air pollution work the odor cannot be turned off during the test. This leads to serious testing obstacles of adaption, fatigue, etc. There are several experimental approaches to this problem: (1) the use of gas masks, to be removed by the subject at the moment of test; (2) the use of "portable" reference air stream, such as can be produced by an activated carbon blower[5]; (3) the use of vapor sampling methods as elaborated in preceding sections to collect odor samples for organoleptic tests. All of these methods merit further study.

In the last analysis, organoleptic tests are the criteria for the effectiveness of any odor abatement method.

Adsorption

The most direct and reliable analytic method to predict the performance and maintenance of activated carbon odor control equipment is that which uses activated carbon test equipment. The test unit shown in Figure 1 contains canisters whose bed thickness is 0.7 in., similar to that used for much of the commercial equipment. Each canister holds 1.5 lbs. of carbon. It has previously been shown[16] that the analysis of such carbon for non-aqueous saturation will give a measure of gaseous atmospheric contamination according to the equation.

$$C_w = \frac{1.67\ (10)^4\ SW}{Qt} \qquad (1)$$

where C_w = concentration of odorants (lb. per million cu. ft.)
S = proportionate saturation of carbon
W = weight of carbon (lb.)
Q = rate of sampling (cfm.)
t = duration of sampling (hr.)

In practice, the sampling unit is allowed to operate in the test atmosphere for a given period. It is then returned to the laboratory for analysis, whereby the value of the saturation, S, is obtained. The concentration of pollutant vapors, C_w, may then be calculated from Equation 1.

To predict the service life (time between reactivations) it is necessary to know the ultimate value of S (retentivity) before the carbon is exhausted. This may be estimated from retentivity tables[11] if the nature of the gases is known. If not, an assumed value of 15 percent is in line with practical experience. Equation (1) may then be solved for t (service life), by substituting known or assumed values for C_w and S. Of course, the value for service life may be obtained more directly by multiplying the sampling time by the ratio of retentivity to analyzed saturation of the test carbon,

$$t = t_o \frac{S}{S_o} \qquad (2)$$

but an independent knowledge of C_w may be valuable when alternate abatement methods are being considered.

During operation of the carbon sampling unit, the effluent air may be sniffed or subjected to more elaborate organoleptic tests for appraisal of deodorizing effectiveness.

Combustion Methods. The critical factors which can be evaluated by analytical methods in odor abatement by combustion are (1) heat value of contaminants, (2) presence of catalyst poisons (where catalysis is used) and, (3) odor changes produced by the oxidation.

A knowledge of the heat value of the odorous gases is essential to the prediction of fuel costs in combustion methods. Fuel costs will be diminished, of course, to the extent that the contaminants contribute heat. This heat value is best measured by a device which uses catalytic oxidation as the test method. There are three types of instruments available or described in the literature: (1) the combustible gas indicator, usually a platinum filament bridge instrument, reads in percent of the lower explosive limit. This gives a good approximation of percent composition from which heat values may be calculated; (2) an instrument recently described[9] which uses a platinum-nickel-chromium catalyst and measures temperature rise, which also may be converted to thermal energy per unit volume; (3) an instrument which permits variation in gas composition, air flow and catalyst, and

(Concluded on page 34)

TVA Air Pollution Studies Program

By Fred W. Thomas
Tennessee Valley Authority
Wilson Dam, Ala.

Steam Plant Construction

Early in 1950 the Tennessee Valley Authority in order to meet greatly increasing power demands initiated construction of a coal-fired steam-electric plant at New Johnsonville, Tennessee. Subsequent to that time construction has been initiated on six additional plants. Scheduled plant capacities range from 450,000 kw. to 1,440,000 kw. In geographical spread these plants are dispersed from the foothills of the Appalachian Mountains to the confluence of the Tennessee and Ohio River Valleys. Terrain ranges from mountainous or hilly in the eastern part of the Tennessee Valley to relatively flat river-floodplain in the northwest portion. Some indication of the range in weather may be illustrated by the contrast in average yearly wind velocity shown in Table I.

TABLE I.

Steam Plant	Average Annual Wind Velocity mph.—1953
Johnsonville	6.8
Widows Creek	6.3
Kingston	4.3
Shawnee	10.3
Colbert	8.3
John Sevier	6.9*
Gallatin	12.6*

*9 Months Record

Planning of Studies

Because of the broad area of uncertainty which still exists regarding diffusion of stack emissions, a study program was authorized to evaluate the expected emissions of SO_2 from the plants so as to identify any needed controls. Consultants with broad experience in the field, and especially in the evaluation of problems associated with SO_2, were retained. From an operations viewpoint, as the several units were put into service, new information of significance pertaining to stack emissions was useful in the planning, design, and operation of other plants.

Studies have been planned and conducted in two distinct phases in each steam plant area: (1) pre-operational and (2) post-operational.

Pre-operational Phase

The pre-operational phase is aimed at establishing baseline information for comparisons with data obtained after operation of a steam plant has been begun. Meteorological installations are made at about the time construction is initiated. This normally assures that two years of record will be available prior to activation of the first generating unit. Inasmuch as TVA maintains rather complete weather records at all major construction projects, it was only necessary to supplement conventional meteorological installations with a Brown temperature instrument and to employ higher masts. Meteorological data obtained include a continuous record of:

(a) Wind direction and velocity at or near elevation of top of stacks,
(b) dry bulb surface temperature,
(c) wet bulb depression for relative humidity,
(d) vertical temperature differential between a point four feet above ground level and a point at approximate elevation of stack top, and
(e) precipitation.

The above data are used in the refinement of initial estimates where little or no weather data were available, in the siting of monitoring instruments, and in the planning of field reconnaissance.

Additional pre-operational work includes information on agriculture and forestry in the area and the collection and chemical analysis of samples from selected species of trees. These data provide helpful guidance in siting monitoring instruments and in evaluating program effectiveness.

Post-operational Phase

After the first unit of a plant goes into service, studies include:

(a) Continued meteorological observations, including use of a pyrheliometer to measure and record solar radiation,
(b) Analysis of data concerning plant operation, e.g., coal consumption and analysis,
(c) Routine monitoring by Thomas autometers,
(d) Biological surveys including sampling and chemical analysis of plant foliage, and
(e) Special studies on dispersion, including
  (1) Determination of effective stack heights
  (2) Downwind ground sampling with mobile equipment to supplement autometer records
  (3) Measurement of total SO_2 activity by oxidation of lead peroxide
  (4) Observation of fly ash control.

The staggered schedule of construction and unit activation has so far permitted a small group to execute both the pre- and post-operational studies described above.

Through a cooperative agreement with the U.S. Weather Bureau, recorded meteorological data are classified and entered on IBM cards for machine analyses. By

this means analyses can easily be made to determine correlation of variables.

Biological Studies

Inasmuch as all the large TVA steam plants are located in rural areas devoted to agriculture or forests, the principal biological study has been with regard to possible effects on vegetation. Experienced biologists have been assigned to careful surveillance of vegetation in the area, to obtain photographs and specimens for future identification, and to evaluate such factors as frost, drought, disease, insect infestation, and emissions from the plant as possible causes for conditions observed. Although this work has been impeded by a severe drought in both the summers of 1952 and 1953, experience has added to confidence in differentiating causes of observed conditions of plant foliage. Several plants which are "sensitive" to SO_2 have been identified and are employed as indicators.

Routine samples of selected deciduous trees (white oak, gum, and tulip tree) have been collected annually just prior to the end of each growing season at Johnsonville, Widows Creek and Shawnee. Normally conifers are sampled during the winter months for better distribution of laboratory analyses. No significant elevation of sulfate has been detected in conifers. Concentrations observed in the foliage of sampled deciduous trees very near the Johnsonville plant have been below injurious levels.

Special Studies on Diffusion

(1) *Determination of Effective Stack Height*

Any investigator is faced with a discouraging number of variables in the theoretical evaluation of diffusion problems, p and q in the Bosanquet[1] equation and n, C_y and C_z in Sutton[2] equations. While uncertainty and lack of agreement regarding the value of these parameters is a source of continuing concern, their significance during light lapse or neutral conditions is dwarfed by the variable H, effective stack height for large steam plants. Our limited experience indicates that stack design should primarily be based on diffusion during average conditions with moderate to high wind speed. At such times mixing is isotropic, and the diffusion coefficients C_y and C_z, and n determine only the location of maximum concentrations. Thus for practical purposes the magnitude of the maximum concentration is independent of these variables.

According to the Bosanquet and Sutton equations in common use for estimating downwind ground concentration of a gas from a known source, the maximum concentration is inversely proportional to the square of the stack height. Early investigators sometimes employed the actual stack height and were probably in no great error for conditions of high wind speed where heat emission was small. However, it is now generally agreed that these equations are only applicable where the effective stack height, which includes the actual height plus the rise of the plume due to velocity and buoyancy, is employed. In 1949 Bosanquet, Carey and Halton[3] offered formulae for use in calculating the velocity and temperature rise of the plume for various conditions of stability and wind speed. Subsequently Sutton[4] advanced a theory for calculating the rise of heated jet in the atmosphere. While it is reported that the Bosanquet *et al* expression has had some confirmation in England, neither theory has been found satisfactory for calculating the rise of a heated plume from a large steam plant with low to moderately high wind speeds. An empirical method which has been found to have considerable value for the Johnsonville steam plant may be of general interest.

This method is based on an analysis of many plume observations made at the Johnsonville steam plant (Figure 1) during 1952 and 1953. Figure 2 illustrates a modified transit which has been employed in making the observations. It consists of a peep site and large ring and cross-wire mounted parallel to the telescope axis. The conventional telescope and cross-hairs do not encompass sufficient plume trajectory for selection of the point of maximum rise. By trigonometric resolution of horizontal and vertical angles, and wind direction from selected observation points as near normal as practical to the plume course, the location and elevation of the observed point of maximum rise is determined. Observations were repeated at about five minute intervals as long as meteorological conditions were reasonably stable, and an average value determined for each set of observations. While it is recog-

Fig. 1. Photograph of Johnsonville steam plant, 1953.

1. Bosanquet, C. H., and Pearson, J. L. *Transactions Farady Society. 32*:1249, (1936).
2. Sutton, O. G. *Royal Meteorological Society Quarterly Journal. 73*:276-281, 426-435, 1947.
3. Bosanquet, C. H., Carey W. F., and Halton, E. M. *Proceedings Institute of Mechanical Engineering.* 162-255-67, 1950.
4. Sutton, O. G. *Journal of Meteorology. 7*:5, 307-312, 1950.

nized that observations are subject to considerable error by the observer as well as in the approximate resolution, confirmation of ground observations in a number of instances by a helicopter flying in the plume lends some confidence.

In Figure 3 those observations which are considered most valid are plotted according to wind speed and order of stability, light and large lapse. These data may be utilized according to a procedure described by Holland[5] to estimate (1) plume rise due to velocity, (2) plume rise due to heat emission, (3) the critical wind velocity, and (4) the maximum downwind concentration. The following stack and effluent parameters are employed in this and subsequent calculations: stack height, 170 ft.; orifice diameter, 14 ft.; exit velocity, 29 mph.; exit temperature, 290°F.; volume emission rate, 395,400 cfm.; heat emission, 46×10^5 calories per second.

While this approach is admittedly empirical, it provides a method for estimating the separate components of the plume rise due to velocity or momentum and heat or buoyancy. Curve 1, Figure 3, represents the rise due to momentum as calculated from the formula of Rupp, Beall, Bornwasser and Johnson[6]. By reference to height of the observed plume it is obvious that this represents only a portion of the total rise. The difference between calculated velocity rise and actual rise may then be assumed to result from the buoyancy component as determined by the heat emission.

In the Rupp *et al* formula, $u\Delta h$ is a constant for each stack. In other formulas commonly employed for calculating the velocity rise, a similar constant relation between u and Δh exists; i.e. $u^{1.4}\,\Delta h$ is a constant in the Davidson formula [7], and $u\Delta h\ (V + 0.43u)$ is a constant for the velocity rise by the Bosanquet, Carey and Halton formula. The velocity components of the plume rise by all of these formulas for wind speed greater than 8 mph. are in quite close agreement. Inasmuch as the Rupp *et al* formula is the most simple, it is most convenient for determining the value of $u\Delta h$ from plume observations. In this expression,

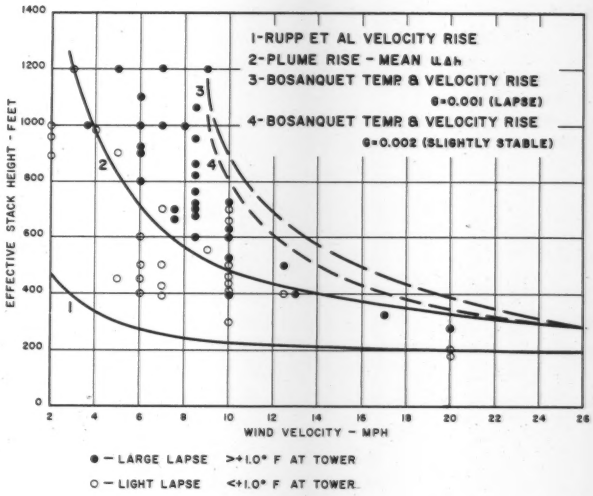
1-RUPP ET AL VELOCITY RISE
2-PLUME RISE - MEAN uΔh
3-BOSANQUET TEMP & VELOCITY RISE
θ=0.001 (LAPSE)
4-BOSANQUET TEMP & VELOCITY RISE
θ=0.002 (SLIGHTLY STABLE)
EFFECTIVE STACK HEIGHT - FEET
WIND VELOCITY - MPH
● — LARGE LAPSE >+1.0° F AT TOWER
○ — LIGHT LAPSE <+1.0° F AT TOWER

Fig. 3. Plume observations—Johnsonville steam plant.

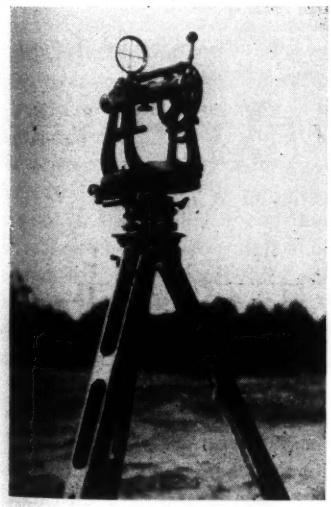

Fig. 2. Modified transit for making plume observations.

Fig. 4. Portable model Titrilog in helicopter.

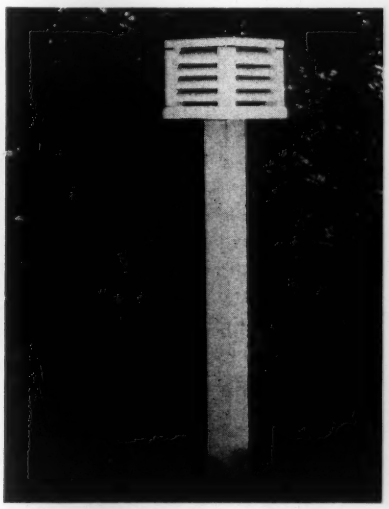

Fig. 5. Lead peroxide cylinder field installation.

5. A Meteorological Survey of the Oak Ridge Area, ORO-99. U. S. Atomic Energy Commission.

6. Rupp, A. F., Beall, S. E., Bornwasser, L. P., and Johnson, D. H. "Dilution of Stack Gases in Cross Winds." (1948) AECD-1811, U. S. Atomic Energy Commission Technical Information Service, Oak Ridge.

7. Davidson, W. F. "The Dispersion and Spreading of Gases and Dusts From Chimneys." (1949) Ind. Hygiene Foundation, Mellon Inst., Pittsburgh, Pa., Trans. Bull. No. 13.

$u\Delta h$ = 1.5 vd, a constant for each stack

h = the plume rise above the stack

where v = stack gas exit velocity

d = diameter of the stack orifice

u = wind speed

$u\Delta h$ = (1.5) (29) (14) = 609

The product, uΔh, for all plume observations and averages obtained under various groupings are given in the following table:

TABLE II—SUMMARY

	uΔh		
	All	Light Lapse	Large Lapse
1— 6	2869 (22)	2208 (14)	4023 (8)
7—15	4054 (42)	3065 (18)	4789 (24)
16—20	1256 (8)	1256 (8)	—
Mean	3381 (72)	2403 (40)	4604 (32)
Median	3420	2317	4430
Standard Deviation	1166		
Standard Error of Mean	137		
1.5vd	609		
6.0 x 10^{-4} Q_H	2772		

TABLE II.
Product of Observed Plume Heights (Δh) and Wind Speed (u)

u	Δh			uΔh		
	All	Light Lapse	Large Lapse	All	Light Lapse	Large Lapse
2	830 (5)	830 (5)	—	1660 (5)	1660 (5)	—
3	842 (2)	1030 (1)	655 (1)	2526 (2)	3090 (1)	1965 (1)
4	805 (1)	805 (1)	—	3220 (1)	3220 (1)	—
5	617 (4)	580 (3)	730 (1)	3085 (4)	2900 (3)	3650 (1)
6	570 (10)	317 (4)	738 (6)	3420 (10)	1902 (4)	4428 (6)
7	480 (8)	331 (6)	930 (2)	3360 (8)	2317 (6)	6510 (2)
7.5	530 (2)	—	530 (2)	3975 (2)	—	3975 (2)
7.7	480 (1)	—	480 (1)	3696 (1)	—	3696 (1)
8.5	628 (10)	—	628 (10)	5338 (10)	—	5338 (10)
9	380 (2)	380 (1)	380 (1)	3420 (2)	3420 (1)	3420 (1)
10	379 (17)	344 (11)	443 (6)	3790 (17)	3440 (11)	4430 (6)
12.5	330 (1)	—	330 (1)	4125 (1)	—	4125 (1)
13	230 (1)	—	230 (1)	2990 (1)	—	2990 (1)
17	130 (1)	130 (1)	—	2210 (1)	2210 (1)	—
20	56 (7)	56 (7)	—	1120 (7)	1120 (7)	—

It is obvious from this table that a large portion of the plume rise as disclosed by the actual value of uΔh is due to heat emission, Q_H or buoyancy. Since the observed values of uΔh do not show a marked variation with the wind speed in comparison with the observations plotted against the wind speed, the mean value (3381) may be considered a constant for the Johnsonville stacks as a first approximation. It is noted that uΔh for large lapse is some 60 percent greater than for light lapse. The stability can be taken into account within the accuracy of the data by adding 10 to 25 percent to the mean for large lapse and substracting a like amount for light lapse. Considering the mean value of uΔh (3381) as the constant for the Johnsonville stacks, the buoyancy component would be

$$u\Delta h - 1.5\ vd = 3381 - (1.5)\ (14)\ (29)$$
$$= 2772$$
$$= 6.0 \times 10^{-4}\ Q_H$$

The formula for average of all observations then becomes

$$h = \frac{1.5\ vd + 6.0 \times 10^{-4}\ Q_H}{u}$$

If stack parameters are lumped in a constant,

$$A = 1.5\ vd + 6.0 \times 10^{-4}\ Q_H$$
$$= 609 + 2772$$
$$= 3381$$

Then the effective stack height = h + Δh

$$h + \Delta h = h + \frac{A}{u}$$

Substituting this value of H in Sutton's formula for maximum ground concentrations, when $C_y = C_z$,

$$C_{max} = \frac{2Q}{\pi e u\ H^2} = \frac{2Q}{\pi e u \left(h + \frac{A}{u}\right)^2} = \frac{2Q}{\pi e}\ \frac{u}{(uh+A)^2}$$

This expression has a maximum at $u = \frac{A}{h}$

$$\text{Where } C_{max} = \frac{2Q}{\pi e}\ \frac{\frac{A}{h}}{(A+A)^2} = \frac{Q}{2\pi e\ Ah}$$

Thus for the Johnsonville steam plant the critical wind speed from all observed plume readings,

$$u = \frac{A}{h} = \frac{3381}{170} = 19.8 \text{ mph.},$$

a value which is in fair agreement with sampling data from all autometers and mobile equipment. However, if the approximation that uΔh is a constant for each stack is accepted, it is believed that selective use of observations in the range of greatest confidence may serve for the best estimate of effective stack height and critical wind speed. In this instance the weakness of observations at low wind speed is evidenced by the wide scatter, and insufficient

observations were made at a higher wind speed. Therefore it would appear preferable to use the 17 observations at 10 mph. where less scatter occurs and where greater confidence can be attached to field observations. For these observations the mean $u\Delta h$ is 3790 and the critical wind speed would be $\frac{3790}{170} = 22$ mph., which agrees very closely with experience at this plant as judged from all sampling and monitoring records.

The expression $H = h_a + \frac{A}{u}$ may be used to develop a curve based on the mean value of all plume observations for various wind speeds, Curve 2, Figure 3. For comparison, Curves 3 and 4 have been developed according to the Bosanquet, Carey and Halton theory for lapse and slightly stable conditions.

This method of utilizing field observational data is useful in that it may be translated to other plants by taking into account differences in design and operational factors, such as exit velocity, stack diameter and heat emission.

Sampling With Mobile Equipment

Much effort and time have been devoted to the development and use of special sampling equipment to supplement the information on SO_2 provided by stationary autometers. Scrubbing devices ranging from nests of midget and large impinger tubes have been employed; a Thomas autometer was mounted in a trailer and attempts made to sample downwind; a conductivity instrument similar to the autometer but employing a Wheatstone bridge and suction from vehicle manifold has been used. None of these devices has provided sufficient information to warrant the effort and expense because of limited mobility, failure to operate reliably for short intervals, lack of access to the course of the plume, and finally failure to provide more than a record of average concentration during the period of sampling.

A portable model Titrilog was therefore obtained in the late summer of 1953. This instrument has been modified for satisfactory operation in a passenger vehicle or in a helicopter (Figure 4). It samples at a rate of about 1000 cc/min. and provides a continuous record which may be reduced by a factor determined through calibration to ppm. SO_2. It also provides a practical solution to the problems associated with other instruments and overcomes the obstacles of access and mobility encountered in hilly, forested and undeveloped terrain.

Experience so far has shown that ways must be found to correlate results using the Titrilog aloft with results obtained by other monitoring techniques. It has shown considerable promise as a means of evaluating theoretical factors involved in dispersion phenomena. While more experience and field data are needed to establish its full usefulness in determining downwind ground concentrations, its applicability for determining axial concentrations, especially during periods of inversion, has been demonstrated.

Measurement of Sulfur Dioxide Activity With Lead Peroxide

An attempt has been made to employ the lead peroxide method developed for economical evaluation of SO_2 activity in large British industrial cities. Basically this method[8] is predicated on the oxidation of PbO_2 to $PbSO_4$ by SO_2 with subsequent chemical analysis at, say, monthly intervals to provide a measure of the total activity of SO_2 during the period of exposure. Figure 5 illustrates one of approximately 25 lead peroxide cylinder installations distributed for a distance of 6 miles around the Johnsonville plant. These cylinders appear to offer a practical and economical means of approximating the cumulative SO_2 activity at a given point and the analytical data may be used to plot an isopleth of total SO_2 activity. In the first installation, the cylinders were not sited in such a way as would permit effective correlation of PbO_2 oxidation with total time-concentration factor, amount of sulfur in plant tissue, or observations of plant foliage. Installations at other plants will be planned so as to facilitate effective correlation of these factors.

Fly Ash

All major steam plants are equipped with mechanical fly ash collectors designed for about 85 per cent removal of fly ash. Most plants are in rural areas and no fly ash nuisance is expected. Provision has been made, however, in the initial design for installation of electrostatic precipitators if they should be required. Shop-made directional deposit gages have been developed and used to classify deposited material according to source direction. This device was developed prior to the more complex directional gage of the Battelle Memorial Institute and does not contain the centering bucket for periods of calm.

Summary

The air pollution control program carried on by TVA has been briefly described. Meteorological and air pollution instrumentations are discussed, and methods of data reduction and analysis described. Specific examples are cited to illustrate studies on effective stack height and diffusion. Information obtained indicates that the effective stack height and critical wind speed can be estimated with sufficient accuracy for practical evaluation of air pollution control requirements.

Acknowledgment

While the Environmental Hygiene Branch of the Division of Health and Safety is responsible for broad planning, special field studies, and evaluation and reporting, important program elements are carried out by other TVA divisions already responsible for similar activities. For example, the Hydraulic Data Branch is responsible for the installation and operation of all stationary instrumentation, such as weather stations and Thomas autometers. The Division of Power Production provides all data on coal consumption and analysis along with asso-

8. "The Investigation of Atmospheric Pollution, Fuel Research Station, Blackwall Lane, Greenwich, London." S.E. 10.

ciated operational data. The Office of the Chief Engineer and the Division of Design conduct economic studies on various stack designs and modification such as constrictors to increase exit velocity of flue gas. The Division of Power Utilization makes economic studies relative to the procurement and utilization of low sulfur coal. Under a special authorization the Office of Chemical Engineering is conducting a research program aimed at development of a practical and economically feasible method of removing sulfur dioxide from flue gases and converting into a useful saleable product.

DISCUSSION OF PAPER BY F. W. THOMAS ENTITLED "TVA AIR POLLUTION STUDIES PROGRAM"

Mr. Thomas has demonstrated in his paper, the value of obtaining pre-operational data as a base line against which actual plant operation may be checked. Further he has indicated how the combination of pre and post-operational studies may be useful in considering the design of other plants having somewhat comparable characteristics.

It is apparent that the broad staffing of TVA has made available to the Environmental Hygiene Branch several facilities and services that are not easily obtained by a municipality or even an industrial concern. The opportunity for research has been used well and others should profit from the findings.

The TVA studies have again demonstrated that theoretical equations of Bosanquet and Sutton cannot be applied blindly to every problem of dispersal of stack gases.

The method of field triangulation of the plume position mentioned in the paper has practical advantages, but in urban situations the physical difficulties of conducting such observations might limit the method.

The critical wind speed has been shown to vary with exit velocity, stack diameter and heat emission. It will also change because buildings and other objects at ground level at or near the stack introduce changes in turbulence. Turbulence is affected by the direction of wind with respect to the point of emission and by the shape of buildings and other configuration adjacent to a stack. Accordingly, the pattern of downwind dispersal will depend on variables which are peculiar to each plant. It is difficult if not impossible to predict the exact effect on critical velocity without a study of the plume over its actual physical site. Such a study establishes critical direction and permits a theoretical approximation of critical wind speed which may be corrected according to available test data. The method offered by Mr. Thomas does not show clearly that critical direction has been considered. It may be assumed that the adjustments in mean value of the constant $u\Delta h$ and the reassurance offered by field test data have neutralized any major error at the plant under study.

It seems prudent to adjust the theoretical considerations on the side of safety when field observations are not available. This means that a critical wind speed higher than that calculated by theoretical means should be used. Mr. Thomas demonstrates this with an adjustment from $u = 19.8$ mph. to $u = 22$ mph., a positive adjustment of 2.2 mph. Four, five or even ten mph. additional might offer a better margin of safety when no confirming data are available and critical downwind conditions exist. Even then the plant should be so designed that stack gas temperature may be raised and stack velocity or stack height may be increased if necessary.

The management of TVA is to be complimented on its constructive plan of air pollution studies and its recognition of the need of air pollution control. Studies described by Mr. Thomas bring practicallity and field utility to the theoretical and sometimes involved procedural aspects of air pollution control.

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College of Engineering,
New York University

Engineers and industrial hygienists who are faced with problems involving the diffusion in the atmosphere of large effluents will follow with interest the program of investigations outlined by Mr. Thomas. The opportunities that are open to the investigator to test at full scale the several mathematical methods that have been developed are unique. As the collection of data proceeds the value of such parameters as C_y, C_z, in the Sutton equations, or $n\Delta h$ in the Thomas equation can be tested.

However, those whose problems lie in congested urban areas or in industrial areas where there are many structures, may be disappointed if they expect that the new data will provide the answer to some of their most difficult cases. The studies outlined here take little or no account of the effects of turbulence generated in the atmosphere by the power station itself or by other structures in the immediate neighborhood, either upwind or downwind. Or, stated in another way, the "aerodynamic effects" have been omitted. This is probably the proper decision for the TVA situation, but it would not be so if the investigation were concerned with the situation in New York City, or probably in most other large cities. In such situations the aerodynamic factors predominate, and the investigator could not ignore the combined effects of the turbulence created by the stack and the station structure. Extensive wind tunnel tests such as those made by New York University for Consolidated Edison Company of New York indicate, with little doubt, that the turbulence created by a station structure with short stacks such as shown in Figure 1 could not be ignored for wind speeds above about 15 miles per hour. That this is not a rare occasion in the New York Area but a common one

Discussion by Dr. Ward Davidson

(Concluded on page 30)

Role of Chimney Design in Dispersion of Waste Gases

By R. H. Sherlock
and
E. J. Lesher
University of Michigan

Studies to determine the laws of behavior of stack gases as they flow downwind, and to prevent downwash of these gases, have been in progress at the University of Michigan since March, 1934, when a project[3-4] in this field was sponsored by the Commonwealth Edison Company of Chicago under the direction of Mr. William L. Abbott and Mr. Alex D. Bailey. That pioneer project was connected with the Crawford Avenue Station and was followed by other studies dealing with the extension of old plants and the design of stacks for new plants. The material presented in this paper was obtained almost entirely from recent studies sponsored by the Commonwealth Edison Company. Some of it has already been presented[1] at the Annual Meeting of the A.S.M.E. in December, 1953, in Paper 53-A-80.

This paper describes remedial measures which may be used in those cases where it is necessary to discharge obnoxious gases into the atmosphere in such quantities that proper dispersion must be assured. Some of the techniques will be recognized as being useful in dealing with some forms of particulate matter.

Influences Acting on Gas Plume

The atmosphere has great capacity to disperse contaminants but there are times and places where this capacity must be used intelligently if trouble is to be avoided. Under favorable weather conditions the plume from a smoke stack will rise gradually as it flows downwind and the gases will be dispersed until only a negligible concentration prevails in the atmosphere. Under such conditions the gases do not become a cause of annoyance to people on the ground. Unfortunately, however, there are several adverse natural influences which arise occasionally to disturb this orderly dispersion of the stack gases.

As the wind flows past a plant it generates turbulence in the wake of the stacks and of the buildings. The turbulent masses of air immediately above and behind the buildings are separated from the smoothly flowing upper layers of air by a vortex sheath, as in Fig. 1(a). If the gases emitted by the stack come under the influence of the turbulence generated by the stack, the gases may be brought down and penetrate the vortex sheath so that they are brought to the ground by the turbulence behind the building. This is termed "downwash" of the gases. Under such conditions the concentrations of obnoxious constituents of the gas on the ground may be very high in the area close to the plant. In general, the term "downwash" will be used to designate that condition in which the bottom of the smoke plume has been forced by aerodynamic causes to descend below some specified height within a distance of about 2000 ft. downwind from the stacks.

If the gas escapes the eddies at the plant it may flow downwind and come under the adverse influence of the terrain. This may be in the form of hills or valleys which set up currents which may entrap the gas.

Even if the gases escape the influence of the eddies near the plant or of the currents deflected by the hills, there are thermal influences in the atmosphere which may bring them to the ground before they have been sufficiently dispersed. These thermal effects cause large scale units of wind structure and these must be superimposed upon the more nearly isotropic elements of diffusion.

Correction of undesirable behavior of gas plumes may be obtained by taking advantage of certain favorable influences which may be used to offset the unfavorable influences just enumerated. These are (1) stack height, (2) gas velocity and (3) gas temperature. There is an economic limit to the height to which stacks can be built. Industrial stacks of a height of 250 to 300 feet are common but are considered quite high. One group of three reinforced concrete stacks which is now under construction will have a height of 680 feet above the ground. These will be the highest in the world and were adopted for an extremely unusual situation.

The influences acting on a gas plume may be summarized as follows:

Influences	
Favorable	*Adverse*
1. Stack height	1. Aerodynamic
2. Gas velocity	2. Terrain
3. Gas temperature	3. Meteorologic

The aerodynamic behavior of the gas plume may be expressed in terms of the ratio of the favorable momentum of the emerging gas to the adverse momentum of the passing wind, both expressed as momentum per unit volume. The relation is not quite linear and its exact form must be established experimentally for each different stack height, and also for the shape and proportions of the

1. "Design of Chimneys to Control Downwash of Gases", by R. H. Sherlock and E. J. Lesher, Paper No. 53-A-80, Annual Meeting A.S.M.E., December 1953.
3. "The Control of Gases in the Wake of Smokestacks", by R. H Sherlock and E. A. Stalker, Mechanical Engineering, June, 1940.
4. "A Study of Flow Phenomena in the Wake of Smokestacks", by R. H. Sherlock and A. E. Stalker, Engineering Research Bulletin No. 29, March, 1941.

plant. Velocities may be used in ratio instead of momenta since this procedure will merely change the shape of the experimental curves which are used to show the functional relationship, provided that the velocities of the wind and the gas are both reduced to equivalent velocities at some standard temperature.

An investigation was made for the purpose of reducing the problem of controlling the downwash of stack gases to a design basis, so that in the future it will be necessary to conduct additional research projects only in those cases where unusual conditions prevail. Only aerodynamic influences were considered as a cause of downwash, since it is one of the adverse influences which definitely can be brought under control and since practically all of the cases of persistent downwash in the immediate neighborhood of most plants are from this cause. However, the other influences are discussed so as to establish their relation to the general problem, and a method of displaying predictions of ground concentrations is shown for a case where such information was of first importance.

A steam-electric power plant is used as a working example. The experiments described in this report were of such scope as to enable the engineer to predict the pattern of stack gas behavior at power plants having a size up to about a half-million kilowatt capacity and where the terrain is not so extraordinary as to constitute a special case.

Diagrams are given which show the dimensions of the hypothetical stations used in the test, together with diagrams of some of the supporting data, and a summary sheet which shows the relation between the wind velocity, the stack gas velocity, the height of stack, the height of the gas plume, and the height of the building.

Only a short description of the testing procedures and equipment is given here since a more complete report of this work will soon appear elsewhere.[2] The future Bulletin will likewise contain additional cases for (1) a variable plant load, (2) a situation where the gases must pass over a moderately high hill, and (3) computation of ground concentrations of SO_2 downwind from the plant.

An illustrative example is given in the form of a case which may arise in plant design. It assumes a plant situated in flat country and operating under full load for the entire year.

Patterns of Gas Behavior

The patterns of flow which may be exhibited by a chimney plume are as varied as the weather and the topography of the nation. A plant may be located in a deep valley or it may be located on level ground. It may be in sparsely settled territory or in the midst of an urban community where there are many obstructions to smooth flow. In approaching a generalized solution of the problem of chimney design it is, therefore, necessary to have some standard of reference.

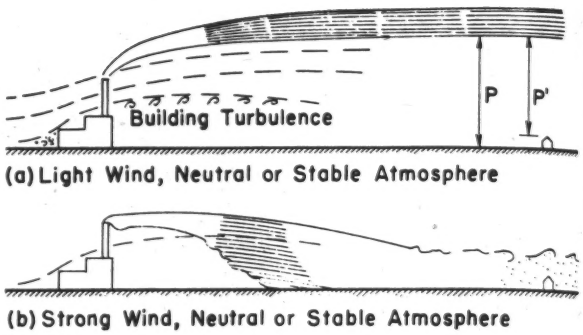


Fig. 1. Basic patterns of gas flow.
(a) Light wind
(b) Strong wind

The Basic Plume

The standard of reference is a location in level open country, and weather conditions which are most easily simulated in the wind tunnel, namely, a neutral atmosphere which is relatively free from vertical mixing. The flow patterns which are shown in the tunnel under these conditions are referred to as "the basic plume". It will be necessary for the designer to superimpose upon the basic flow patterns the effects of dispersion and diffusion, unfavorable terrain, and gas temperature.

Fig. 1(a) shows the free flowing plume which occurs with high stack gas velocity in a light wind, and Fig. 1(b) shows the downwash which may occur with low stack gas velocity in a strong wind. It should be noted here that aerodynamic downwash will usually occur in two steps, the first of which is caused by the eddies at the tip and in the wake of the stack.[3] If this first step brings the gases low enough so that they penetrate the vortex sheath over the building turbulence, the gases may be brought to the ground.[4]

The wind tunnel results must be supplemented by a decision as to the clearance which the bottom of the basic plume must have above the ground or other objects to be cleared by the gases. These clearances are shown and P and P' respectively in Fig. 1(a). Usually the question which the designer must answer is this: "How much clearance must be allowed between the basic plume and the ground or other obstructions, in order that diffusion may reduce the concentration of obnoxious constituents of the gases to within tolerable limits before they reach the ground?"

Dispersion and Diffusion of Stack Gases

Fig. 2 pictures the principal patterns of dispersion which need to be superimposed upon the basic plume shown in Fig. 1. Fig. 2(a) simulates the idealized diffusion which is assumed in the equations of Sutton[5], and others[6]. Isotropic turbulence is also usually assumed,

2. "Design of Chimneys", by R. H. Sherlock, Engineering Research Bulletin No. 38, 1954, University of Michigan, Ann Arbor, Michigan.

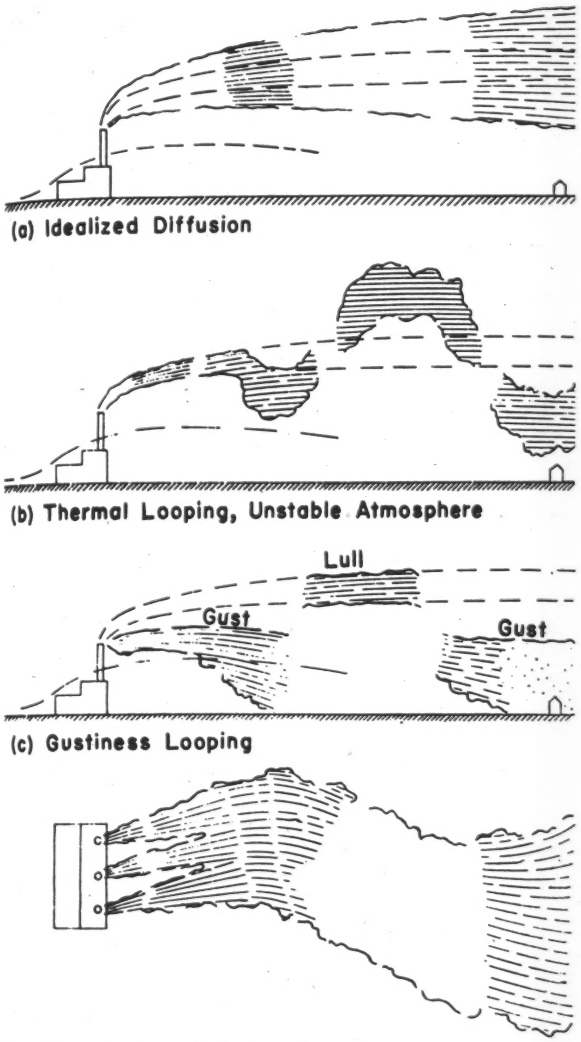


Fig. 2. Some patterns of gas dispersion
(a) Idealized diffusion
(b) Thermal looping, unstable atmosphere
(c) Gustiness looping
(d) Meandering of gas plumes

that is, the same coefficients of diffusion are ordinarily used both vertically and horizontally.

Obviously the foregoing assumptions are useful only if the coefficients can be made to approximate the actual conditions in nature reasonably well. There can be no doubt that isotropic turbulence rarely, if ever, occurs in nature except to a very small scale, and that major elements of wind structure occur frequently, as shown in Fig. 2(b), 2(c), and 2(d). This is especially true in an unstable atmosphere, that is, one in which the decrease of atmospheric temperature with height is greater than the adiabatic lapse rate. Vertical convection cells are common and the resulting shape of plume is usually referred to as thermal looping, shown in Figure 2(b). These convection cells frequently extend to the ground and may extend upward hundreds or in some cases even thousands of feet. Their effect in dispersing the gases is very great, but unfortunately they frequently bring the gases to the ground before the concentration of obnoxious constituents has been reduced within satisfactory limits.

Another form of looping is due to rapid changes in the horizontal component of wind velocity, or in more common terms, due to gustiness. When the stack gas velocity and the average wind velocity are such as to permit the basic plume to travel along a satisfactorily high path, there may occur gusts of such intensity that the plume will be brought downward, even to the ground, as shown in Fig. 2(c). It may be questionable whether gustiness looping and thermal looping ever occur separately, but it is certain that there are times when one is so dominant that the other cannot be distinguished.

In addition to the vertical components of wind structure there are also horizontal components, which cause meandering of the gas plumes as shown in Fig. 2(d). This component likewise produces dispersion which tends to reduce the concentration of obnoxious constituents of the stack gases, although in a temperature inversion it is possible to have meandering with very little diffusion.

Unfavorable Terrain

Because they require large amounts of water many power plants are placed close to the edge of a bay, a lake, or a river. Under such conditions the plant may be located on low land with a hill or bluff not far distant. When the wind is blowing toward the hill it will be deflected upward and the height to which this deflection extends may be two or more times the height of the hill. If the plume approaches the hill at a height sufficient to escape the turbulent boundary layer on the surface of the hill it may actually be deflected upward and escape contact with the hill. However, unless the surface of the hill is very smooth, a turbulent boundary layer will be built up which may extend to a considerable height, particularly if the face of the hill is covered with a growth of rugged trees. In that case the turbulent boundary layer may have a depth of 75 or 100 ft. above the ground. On the other hand, if there is a dense growth of bushes or samplings on the face of the hill a strong wind may very well have the effect of streamlining the direction of the small branches and leaves so that the overall effect is one of smoothness rather than roughness.

Fig. 3 shows a very unfavorable situation with regard to the terrain. A basic plume has undergone a more or less idealized degree of diffusion as it approaches the hill. The bottom of the plume is not high enough to escape the turbulent boundary layer with the result that

5. "The Theoretical Distribution of Airborne Pollution from Factory Chimneys", by O. G. Sutton, Royal Meteorological Society, Quarterly Journal, 1947, Vol. 73, p. 426.
6. "The Spread of Smoke and Gases from Chimneys", by C. H. Bosanquet and J. L. Pearson, Trans. Faraday Soc., 1936, Vol 32, p. 1249.

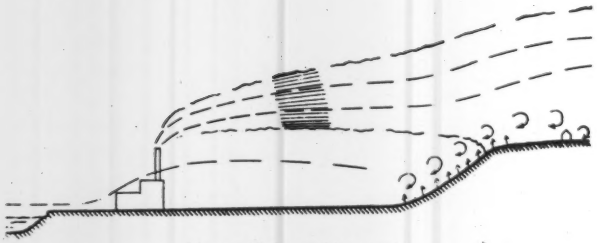


Fig. 3. Unfavorable terrain.

the bottom of the plume performs the familiar "diving" into the face of the hill.

Gas Temperature

In modern power plants the gases leave the stacks with temperatures from 250° to 375°F. The temperature of the plume decreases rapidly due to diffusion in the ambient atmosphere. However, the flotational effect of the high temperature is not lost because, although the temperature of the gas plume decreases rapidly, the overall heat content of the mixture of gas and air is not reduced. The theoretical rate of rise has been computed but, here again, as in the case of idealized diffusion, the basic assumptions are only a rough approximation to nature. However, in computing the ground concentrations during the low wind velocities of a "break-up" of a ground inversion, the theory is the best basis available for determining the plume height.

In those cases where the plume has not escaped the adverse aerodynamic effects around the stack and in the wake of the building, or has not escaped the turbulent boundary layer at the face of a hill, the flotational effect of hot gas temperatures offers very little in the way of a remedy.[2] However, in situations where the stacks are very high and the plume is not likely to be entrapped in the turbulence of the hill, the temperature of the gas may be ignored in the calculations and considered simply an additional item of safety, since it will increase the distance the plume will travel before diffusion brings it to the ground, and it will therefore decrease the concentration of the gas before it reaches the ground.

Combined Effects

The basic plume in a neutral atmosphere serves as a satisfactory standard of reference to which other effects may be added. The most difficult of these effects to determine quantitatively are dispersion and diffusion. Extensive investigations are now in progress in an attempt to evaluate these effects. Some results have already been published[8] and it is hoped that this aspect of the problem will be in better shape for the designer in the relatively near future. Complete information regarding the dispersion of stack gases requires that a statement of the concentration with which gases reach the ground be supplemented by a statement of both the probable frequency and duration of these events.[9] High concentration for short periods or low concentration for long periods may be equally deleterious.

The effects of unfavorable terrain can be anticipated on the basis of observations in the field and on the basis of well controlled experiments in the wind tunnel. However, for a situation like the one shown in Fig. 3, it is well to resort to a special research program in the wind tunnel. For any given size of wind tunnel there is, of course, a limit to the height of hill which can be investigated without using a model which is so small that the results would be questionable. A situation involving a hill will be published in a future bulletin.[2] The experiments reported herein were performed with cold stack gases at a velocity which gives the same exit momentum per cubic foot as the hot gases at the plant. The flotational effect of hot gases is ignored, but this is of small effect close to the plant and it is on the safe side to ignore it.

Wind Tunnel

The investigation was conducted at the University of Michigan in a wind tunnel which is 8 ft. wide by 5 ft.

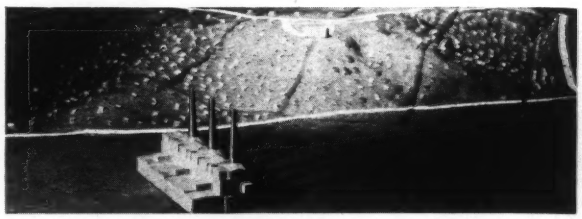
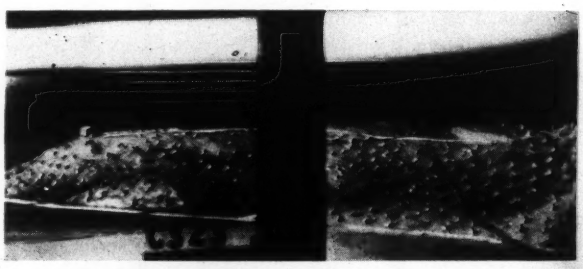


Fig. 4. Wind tunnel set-up, unfavorable terrain
(a) Looking downwind



(b) Free-flowing basic plume

(c) Downwash

8. "Relation of Gustiness to Other Meteorological Parameters", by M. E. Smith and I. A. Singer, J. of Meteorology, Vol. 10, No. 2, April, 1953, pp. 121-126.

9. "Analyzing Winds for Frequency and Duration", by R. H. Sherlock, Meteorological Monograph No. 4, November, 1951, pp. 42-49, American Meteorological Society.

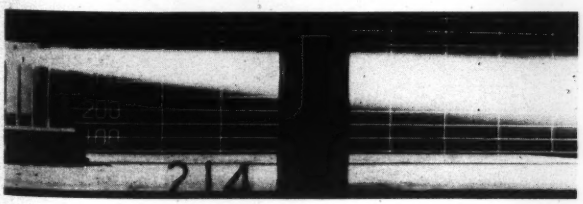
high, with a venturi working section approximately 14 ft. long, as shown in Fig. 4(a). The velocity of the approaching undisturbed wind was always kept at 20 ft. per second. The smoke consisted of a mixture of oil vapor and steam and was emitted from the stacks at a temperature of 70°F. The desired changes in the ratio of the gas velocity to the wind velocity were obtained by varying the gas velocity. The smoke plume was photographed through a plate glass window against a grid on the far side of the tunnel and with an exposure of one second (Fig. 4 and 5). This was too long an exposure to show the structure of the plume. Instead, it gave an integrated history of the plume for a period of five minutes at the plant site and made it possible to choose envelopes which were representative of the position of the basic plume with each particular velocity-ratio.

The Model

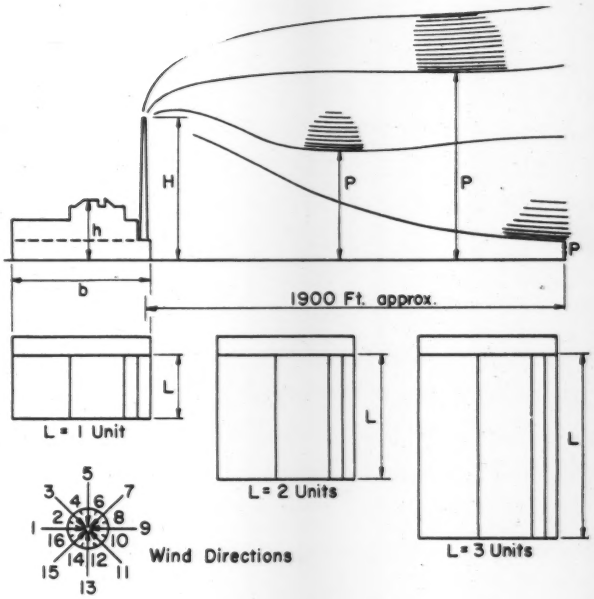
Fig. 6 shows the shape and proportions of the hypothetical station building used in the wind tunnel tests. Its profile is roughly streamlined and the stacks are set on one of the lower levels of the roof. This profile may be looked upon as being unusually well shaped for the purpose of minimizing downwash from aerodynamic causes. It will also be noted that the length of the building is given in terms of units, each unit of length being 150 feet and corresponding to a hypothetical plant capacity of 150,000 kilowatts. This length of 150 feet for a 150,000 kilowatt plant may seem large, but it is on the safe side for two reasons, namely, the total momentum of the emerging gas per unit of the building, and the aerodynamic deflection of the passing wind. The greater the volume of building for a given rate of gas discharge the greater will be the deflective effect upon the plume. The position of the basic plume is identified by the minimum height to the bottom of the plume within approximately 2,000 ft. downwind.

The model was made to a scale of one to three hundred. The smoke was transmitted through a measuring orifice

Fig. 5. Wind Tunnel set-up, level terrain
(a) Free flowing basic plume



(b) Downwash



H = height of stacks (250', 300', 350', or 400')
h = " " building = 125'
b = width " " = 290'
L = length " " = 1, 2, or 3 Units where each unit of length is 150 Feet for 150,000 Kw. of station capacity.
P = lowest height of smoke plume in 2000'±.

Fig. 6. Shape and proportions of hypothetical plant.

into a stilling chamber in the plant model and thence to the stacks. The center stack was always placed on the centerline of the tunnel and the grid on the far wall measures the height of the gas plume along that line.

Test Results

Only sample test results from the supporting data can be given in the limited space of this paper.

Fig. 7, 8 and 9 are typical of the manner in which the original wind tunnel data were plotted. In each diagram the height of the plume was plotted against the velocity-ratio, that is, the velocity of the stack gases to the velocity of the wind, both being reduced to equivalent velocity at 70°F. This gives the ratio of the favorable momentum of the stack gases to the unfavorable momentum of the wind. It is important that these velocities be always referred to these standard conditions rather than to the operating temperatures. Since the building is never perfectly symmetrical with respect to the direction of the wind, it is inevitable that there will be differences in the behavior of the stack plume for different wind directions. Also there will be some experimental errors. This means that in Fig. 7, the results for directions 1 and 9 will show some differences. Nevertheless, for sake of simplicity these two directions were combined and a curve fitted to the average position of the experi-

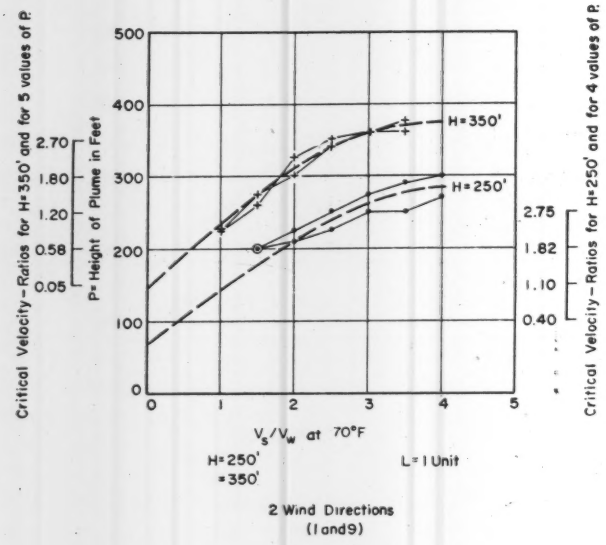


Fig. 7. Original data.

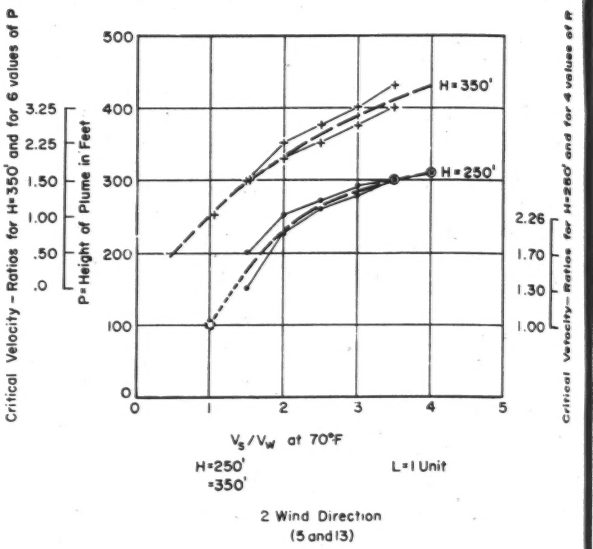


Fig 9. Original data.

mental points. In some cases a mathematical curve was used but in others a curve was merely fitted by eye. An additional vertical scale is shown at each side of the diagram for convenience in transferring readings to the next set of diagrams.

Fig. 8 shows the experimental data for winds blowing diagonally across the plant where the departure from symmetry for each wind direction is much greater than in the previous case. The experimental data show a correspondingly greater degree of dispersion. Nevertheless, the data were combined into one diagram for each stack height and a curve fitted to the data. In like manner Fig. 9 shows the experimental data for the two wind directions along the axis of the line of stacks.

Fig. 10 to 13 give, for 16 wind directions, the relationship between critical velocity ratios, height of stack, height of plume, and for a plant building 2 units (300 ft.) long. Similar diagrams are available for buildings one unit (150 ft.) and 3 units (450 ft.) long, but they are omitted here. In Fig. 12 the values are shown for a stack 350 feet high. These diagrams are intended to be

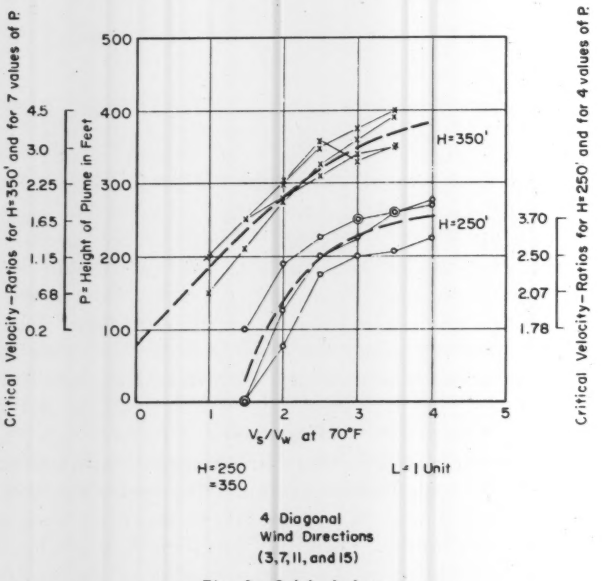


Fig. 8. Original data

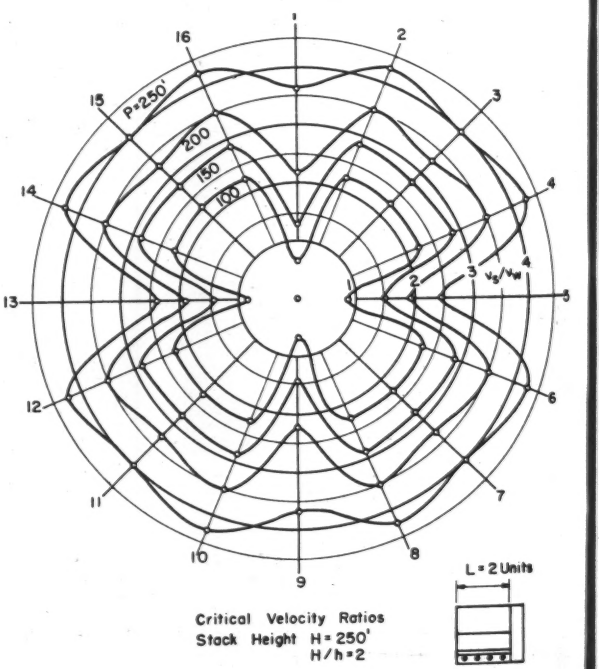


Fig. 10. Critical velocity ratios $\frac{V_s}{V_w}$

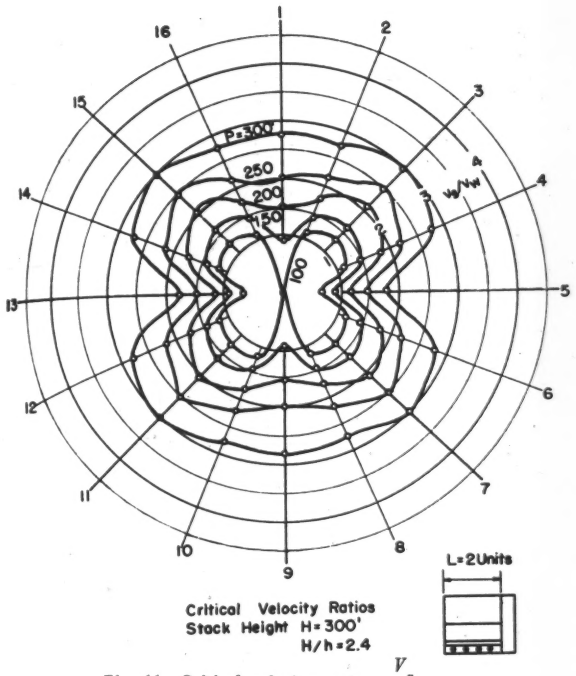


Fig. 11. Critical velocity ratios $\frac{V_s}{V_w}$

used for design purposes. The range of conditions is adequate for all except very unusual cases. For example, the ratio of the height of stack to the height of building varies from 2:1 to 3.2:1.

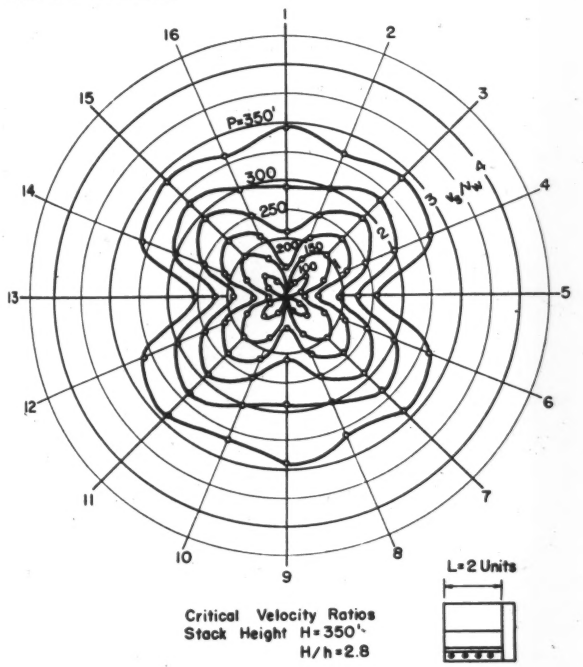


Fig. 12. Critical velocity ratios $\frac{V_s}{V_w}$

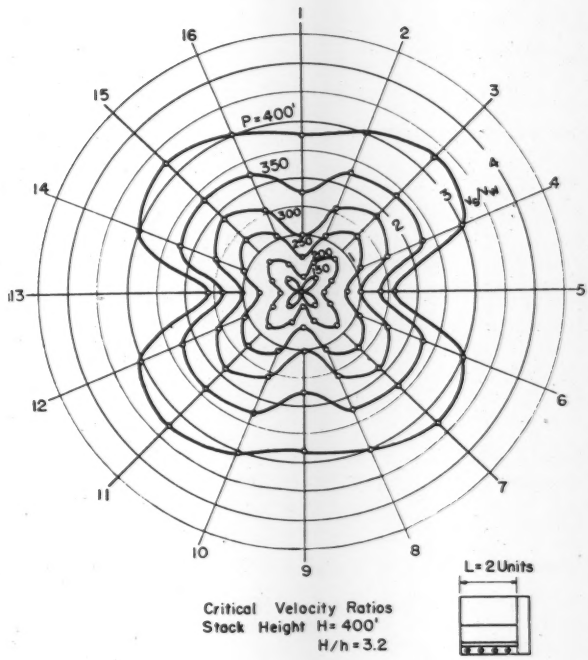


Fig. 13. Critical velocity ratios $\frac{V_s}{V_w}$

Illustrative Case

The following example is given to illustrate the manner of using the diagrams for design purposes.

A proposed power plant has a main building which is 280 ft. long, 285 ft. wide, and 130 ft. high to the parapet of the houses above the main roof. At a full operating load of 300,000 kw. the temperature of the stack gas will be 335°F., and the velocity of discharge will be 60 fps. The axis of the line of stacks, two in number, is on an east-west line, and near the south side of the plant. The roof is free from such obstructions as tanks, ventilating monitors, bins, dust collectors, etc., so it may be said that the roof presents no unusual aerodynamic conditions. However, unlike the test models, the north, south, and west walls are unbroken from the ground to the main roof line, so that they present a high blunt surface to deflect the wind upward and sidewise. The east wall is broken by an auxiliary building which is 50 ft. high, 60 ft. wide (E to W) by 280 ft. long (N to S). The east wall, therefore, like the test models, presents a more favorable exposure from the standpoint of deflection than do the other three exposures.

The plant is located on a level plain and it has been decided that the height to the bottom of the basic plume, P, must be equal at least to 150 ft., if the concentration of obnoxious constituents of the stack gas is to be kept within tolerable limits at the ground level.

Compute the probable number of hours per year that the bottom of the basic plume will be below 150 feet, in each of the eight cardinal segments of the compass, if the stack height is 350 ft. from the ground, and full operating load is assumed for the entire year.

Solution

Refer to Fig. 6. It will be seen that the proposed plant is similar to the test models which had a length of two units, except that the proposed building cross-section is less favorable from the aerodynamic viewpoint. This latter difference will be ignored in the computations and an arbitrary adjustment will be made at the end of the computations.

Refer to Fig. 12 which is drawn for a stack height of 350 ft. and a building length of two units. It shows the critical velocity-ratios ($V_s \div V_w$ at 70° F) necessary to keep the bottom of the basic plume above each of six different heights, and with the wind blowing from each of sixteen directions. Consider the wind to be blowing from the southwest, that is, from direction 11 of Fig. 6. The critical velocity-ratio, below which the bottom of the basic plume will be lower than 150 ft., is 1.0. But this ratio is applicable to only a small angle of the compass. A deviation from the southwest of only 22½° will reduce the critical velocity-ratio to about 0.7. Since the area around the plant is being divided into eight angular segments, the southwest segment, therefore, will be bounded by directions 10 and 12, and the average critical velocity-ratio for this segmental area will be $(10 + 0.7) \div 2 = 0.85$. Call it 0.9. This result is entered in Table I along with similar results for the other segmental areas.

In order to complete the table the velocity of the gas must be reduced to equivalent velocity at 70°F, thus:

$$V_s = 60 \frac{70 + 460}{335 + 460}$$

$$V_s = 40 \text{ fps.}$$

Since the value of V_s is known, the critical value of the wind velocity, above which the bottom of the basic plume will have a height less than 150 ft. can be computed.

$$V_w = \frac{40}{0.9} = 44.4 \text{ fps.}$$

$$V_w = 30.4 \text{ mph.}$$

This is the critical wind velocity and it is entered in the proper compartment of the table under "southwest" and opposite V_w.

It is now necessary to find the probable number of hours per year when this velocity will be exceeded, based on the previous history of the wind in this area. Fig. 14 gives this information for one location. It will be seen that during 0.04% of the hours in an average year the wind will be blowing from the southwest with an

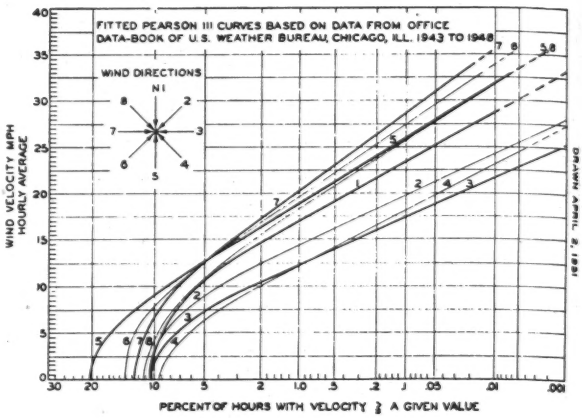

FITTED PEARSON III CURVES BASED ON DATA FROM OFFICE DATA-BOOK OF U.S. WEATHER BUREAU, CHICAGO, ILL. 1943 TO 1948
WIND DIRECTIONS
N1
WIND VELOCITY MPH HOURLY AVERAGE
PERCENT OF HOURS WITH VELOCITY ≥ A GIVEN VALUE
DRAWN APRIL 2, 1951

Fig. 14. Six year wind records.

hourly average velocity equal to or greater than 30 mph. This gives 3.5 hours of "downwash" per year. Enter these two values in the table. Repeat the computations for

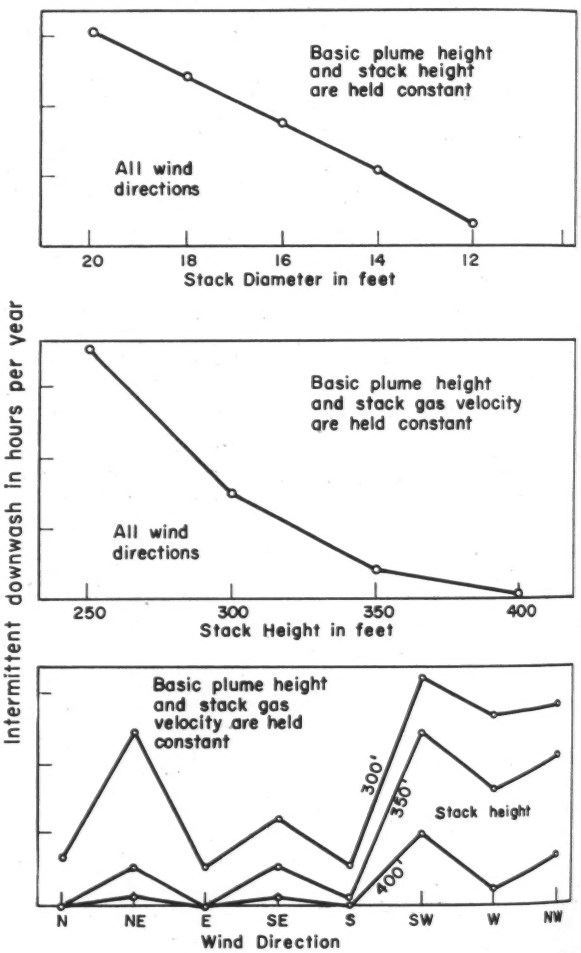


Fig. 15. Downwash vs. stack height, gas vel., wind direction.

each of the other seven segmental areas of the compass. The total hours of intermittent "downwash" per year is 5.3. In this case it means 5.3 hours when the bottom of the basic plume will be intermittently less than 150 ft. above the station yard, in the 45° segmental area northeast of the plant. The word "intermittent" is used for clarity since, during most of these hours, the wind velocity will be sometimes above and sometimes below the critical velocity.

If the computations are repeated for other heights of stacks and other velocities of discharge of stack gas, diagrams can be drawn to show the relationship between downwash and height of stacks, and also between downwash and gas velocity, as shown in Fig. 15. These will enable the designing engineer to choose a satisfactory height of stack.

The results in Table I are based upon a test model of a plant building having a most favorable profile from the aerodynamic viewpoint. As stated previously, the building for the illustrative case is somewhat less favorable because of the blunt exposure of the walls in three directions. Tunnel tests have shown that such adverse differences in the building shape may require an addition of about 25 ft. to the height of the stack in order to obtain equal performance, except in those cases where the ratio of stack height to building height is large enough to eliminate the effect of building shape. There is also the slightly less favorable condition that the height of this building is 130 ft. instead of the 125 ft. used in the tests.

Atmospheric Dispersion of The Basic Plume

The illustrative problem has not been carried to the point where probable ground concentrations of SO_2 are computed, but a short discussion of that subject is given here. Fig. 16 is a perspective drawing showing the relation between the basic plume and the ground concentrations downwind under the center-line of the plume. It also shows the manner in which the concentrations occur to both sides of the plume as the result of lateral dispersion. The equations of Sutton[5] and others may be used

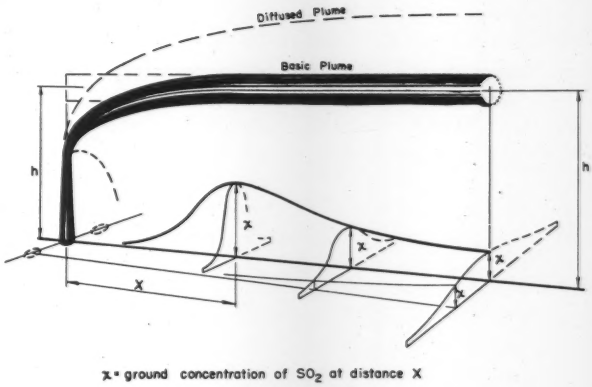


Fig. 16. Ground concentration of SO_2 at distance x.

to compute the concentrations at different points on the ground provided that the proper diffusion parameters are known for the particular situation that exists in any case. The best empirical information in regard to the proper value of these parameters is to be found in the work of E. Wendell Hewson,[7] at Round Hill Observatory and M. E. Smith,[8] at Brookhaven, Long Island. However, the diffusion parameters will be largely affected by the turbulence behind the stacks and buildings, and neither of these investigations include such turbulence in their observations. There is a need for investigations of this nature to be made at actual plants in operation.

Break-Up of Temperature Inversions

During the night and early morning temperature inversions may occur as the result of the radiation of heat from the ground. If the night is clear and the wind is light the inversion may have a depth of several hundred feet. Due to the great stability of the atmosphere in an inversion there is very little vertical mixing and the plume will pass slowly downwind as a shallow ribbon which

7. "Research on Turbulence and Diffusion of Particulate Matter in the Lower Layers of the Atmosphere", by E. Wendell Hewson, H. E. Cramer, G. G. Gill, and F. A. Record, 1951, Final Report Contract No. AF28(099)-7, Geophysics Research Directorate, Air Force Cambridge Research Center.

TABLE I.

Intermittent Downwash (150′—) in Hours per Year — Based on Wind Velocities 1943 to 1948

FULL LOADING CONDITION

Wind Direction	N	NE	E	SE	S	SW	W	NW	V′ 335° Fps.	V_s 70° Fps.	$\frac{H}{h}$	H Height Ft.
$V_s \div V_w$	0.4	0.9	0.5	0.9	0.4	0.9	0.5	0.9	60	40	2.8	350
V_w (mph)	68.2	30.4	54.6	30.4	68.2	30.4	54.6	30.4				
% Hours	—	—	—	—	—	0.04	—	0.02				
Hours per Year	—	—	—	—	—	3.5	—	1.8				

undergoes practically no vertical dispersion. Such plumes have been followed downwind for many miles. A certain amount of meandering may occur together with some slight lateral spreading. Under such conditions the concentration of the gases in the plume will remain very high.

After sunrise the ground is again heated and a layer of warm air is formed near the ground. The thickness of the layer of newly formed turbulent air increases until it eventually envelopes the plume. The vertical mixing brings the gas to the ground in high concentrations. Very little experimental information is available regarding these concentrations and any computations must be based upon assumptions which may be plausible but whose validity are not well established. Nevertheless, it is sometimes necessary to make these plausible assumptions and to proceed with the computation of probable ground concentrations from this source.

Ground Concentrations of SO_2

Table II illustrates the manner in which information regarding ground concentrations may be tabulated. It shows the hours per year when the concentration of SO_2 lies within indicated limits for a particular segmental area to the leeward of the plant. The boxes near the left-hand side of the table contain the number of hours of a given concentration obtained by applying Sutton's equation in the manner indicated in Figure 15. The diffusion parameters were obtained from several sources, some of which are unpublished. The total number of hours per year that the wind will carry the plume into this particular segmental area is 785. It will be seen that the higher stacks have a tendency to place all of the hours of this particular wind direction in the lowest category of concentration. The 3.8 hours per year are due to the fumigation which is coincident with the break-up of ground inversions in the morning.

Summary

A method has been developed for the use of wind tunnel testing of models by which the design of a station building and its stacks can be determined so that the downwash of the smoke plume towards the earth due to aerodynamic effects, can be practically eliminated. Knowledge gained in the wind tunnel concerning the behavior of the plume close to the plant can be used as a starting point for the computation of ground concentrations of gas. The results will be more reliable than those based on the usual assumption of a point source.

DISCUSSION OF PAPER BY SHERLOCK AND LESHER ENTITLED "THE ROLE OF CHIMNEY DESIGN IN THE DISPERSION OF WASTE GASES"

The wind tunnel is recognized as a most valuable experimental tool, and it has unquestionably contributed to very important advances in aerodynamics. The device has two most appealing advantages; it permits the testing of models rather than full scale units, and the investigator can often *see* the results of design alterations prior to construction.

TABLE II.

Stack Height = 576′ Dist. downwind, Miles	ppm 1	2	3	4	5	9
2	785			3.8		
2	785				3.8	
1	785					3.8
1						
0						

Stack Height = 504′ Dist. downwind, Miles	ppm 1	2	3	4	5	9
2	785			3.8		
2	785				3.8	
1	785					3.8
1						
0						

Stack Height = 432′ Dist. downwind, Miles	ppm 1	2	3	4	5	9
2	785			3.8		
2	614	171			3.8	
1	479	306				3.8
1						
0						

Stack Height = 360′ Dist. downwind, Miles	ppm 1	2	3	4	5	9
2	439	346		3.8		
2	103	682			3.8	
1	76	169	540			3.8
1						

No data shown between 5 ppm. and 8 ppm.

No data shown over 9 ppm.

NOTE: Hours per year when the concentration of SO_2 in ppm. by volume lies within the limits indicated for each 22.5° segmental area to the leeward of the plant. Stack Gas Velocity = 60 fps. Wind from SW.

However, there is an important restriction on the use of wind tunnels in that the *proper scale factors* must be used in order to achieve good simulation. The full-scale design changes based upon tunnel tests *may* by chance alleviate a meteorological problem, even though the latter has not been simulated at all well in the tunnel.

The dispersion of stack effluent in the atmosphere is an extremely complex process in which a very wide variety of factors are important. The process may be broken down in a somewhat oversimplified fashion into three problems, in each of which particular factors seem to be especially important.

The first has been described as the *aerodynamic* prob-

lem, in which eddies in the wind flow are generated by the terrain and structures in the immediate vicinity of the stack, and by the stack itself. The most important factors here are the structural shapes, the wind direction and the wind speed, and it is certainly possible to achieve excellent simulation of the "aerodynamic problem" in the wind tunnel.

The second problem is concerned with the *buoyancy and jet effects* associated with the stack gas emission. In this, a larger number of factors are important, including the stack parameters of speed, density and volume of emission as well as the meteorological factors of wind speed, vertical density structure, and probably to a lesser degree atmospheric turbulence and wind shear. Many attempts have been made to simulate these effects in the wind tunnel, but to date no complete experiment relating field and tunnel tests has been undertaken. At present, it is not possible to show that the simulated rise of stack gases in the wind tunnel is significantly better than a purely theoretical calculation of the rise of the plume.

The third problem, *meteorological dispersion,* relates to the diffusion of smokes and gases in the natural atmosphere. This part of the process is primarily dependent upon wind speed, wind shear, vertical density structure, and terrain features. To date, only one wind tunnel has been constructed[1] with the specific idea of simulating such factors as the density structure and the wind shear, and even this has never been subjected to appropriate tests to assess its capabilities.

Thus, the major criticism of the paper under discussion lies in the unjustified assumption that the effectiveness of the wind tunnel is limited only by its size in relation to that of the area to be investigated. The tunnel also loses its effectiveness when the area and terrain features under investigation become so large that meteorological, not aerodynamic factors are dominant. This is certainly true of the main example given in the paper (Figure 3).

The authors refer to a plant site involving a nearby hill or bluff, describing an upward flow of air over the bluff, a turbulent boundary layer having a depth of 75 or 100 ft. above ground and a "familiar diving" of the smoke plume into the face of the bluff if it is caught in the boundary layer. These features may be obvious in the wind tunnel, but there is no justification for assuming that they occur in nature. Field investigations have certainly not shown a definite boundary layer of this extent and type. The "diving" effect is by no means "familiar", nor can we be certain of the extent of any upward flow of air over the hill. Under a temperature inversion, this is probably non-existent.

The authors, of course, have not claimed that the tunnel will simulate meteorological effects completely, but rather that the conditions most easily simulated is a neutral atmosphere, and that upon this "basic plume" one must superimpose the effects of dispersion and diffusion, unfavorable terrain, and gas temperature. They further state that the basic plume in a neutral atmosphere serves as a satisfactory standard of reference. No proof has been given that the neutral atmosphere can be simulated easily, nor is any indication given of the procedure to be used in "superimposing the effects of dispersion and diffusion". Furthermore, the writers of the present discussion have devoted an entire paper[2] to the thesis that a neutral atmosphere does *not* constitute a satisfactory standard of reference. Typical meteorological conditions alternate between significant thermal instability during the daytime and marked temperature inversions at night. Neither condition is easily simulated in a wind tunnel.

Exception must also be taken to the statement that "the best empirical information in regard to the proper value of these (diffusion) parameters is to be found in the work of . . . M. E. Smith[8], at Brookhaven". Neither this reference, nor any other publication of the present writers contains a recommendation of values to be used for the parameters of the diffusion equations. There has been more than enough misunderstanding and misuse of data in this complex field, and no recommendation of specific values for the diffusion parameters will be published by the Brookhaven group until current experiments provide ample *proof* that these values constitute a significant improvement over already published data.

It would be possible to agree completely with the author's summary if the paper had dealt with aerodynamic problems in the true sense. However, they have extended their treatment to include flow problems in which meteorological effects are dominant. For this reason, their conclusion that the wind tunnel test can serve as a starting point for the computation of ground concentrations of gas, and that the results will be more reliable than point source computations cannot be accepted at its face value. A given air pollution problem may be primarily aerodynamic, primarily meteorological or an intricate combination of the two. Where the central problem is actually aerodynamic, the wind tunnel unquestionably provides the best solution. However, if the problem is basically meteorological, wind tunnel tests are of little value and may fail completely in revealing important aspects of the situation.

The most sensible approach to any specific pollution problem would consist of a careful preliminary study by qualified persons to determine what detailed tests and analyses are indicated. On the basis of this, either wind tunnel tests or meteorological analyses or a combination of the two might be undertaken. In a significant number of cases, the preliminary analysis itself might be sufficient to suggest the appropriate remedy.

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Important Considerations in The Use of The Wind Tunnel For Pollution Studies of Power Plants*

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The wind tunnel is a tool by which air flow phenomena occurring in nature may be reproduced to a smaller scale in such a manner that observations made in the tunnel can be interpreted in terms of full scale.

During the past several decades, intense research in the application of the wind tunnel to aeronautical problems has so firmly established its reliability in that field, that tunnel tests are now routine for all aircraft in the first stages of design. This acceptance is so widespread that one is tempted to use the tunnel to study other air flow phenomena not encountered in the aeronautical field. Such practice may often be fruitful, but it may also be misleading, since these other phenomena may be sensitive to different variables. The diffusion of gases from power plant stacks into the atmosphere is one of these fields.

The aeronautical tunnel uses one medium, usually air, homogeneous in velocity, temperature and turbulence throughout the working section. The principal function is to permit observation of forces on an object in the air stream. A tunnel which would be suitable for diffusion studies may require two fluids, gas and air, of different physical properties, temperature and velocity gradients, and a variety of turbulent eddy sizes. Its function would be to permit observation of the gas motion.

It is apparent from even a cursory glance that the physical dimensions, operating characteristics, auxiliary controls and instrumentation of the two types of tunnels must be different, the latter being a good deal more complex.

More important still, the two types of tunnels use different laws of similitude.

Since there appears to be a pronounced interest in the wind tunnel as a test medium for power plant diffusion problems, it may be of value to describe and evaluate the phenomena which it is capable of reproducing. This paper will discuss the theoretical considerations, a test in a wind tunnel designed specifically for diffusion studies, and limited confirmation of the test results by comparison with field data.

Theoretical Considerations

The Problem

The most common problem brought to the wind tunnel by industrial units is the descent of gases to the ground after emission from stacks. Usually, the only evidence of such ground contamination is a number of complaints from local residents summarized in a map showing the area around the plant from which the complaints arise. Sometimes wind roses are supplied showing the frequency of winds of different speeds in the various compass directions, obtained from a nearby weather station. Occasionally, a company will have sampled concentrations around the plant over a period of time.

The picture thus presented usually shows that the complaint area is confined to a sector which receives the plant stack gases at times of strong winds. The request is made to determine the effectiveness of several corrective measures to keep the gases clear of the complaint area.

The ambiguous word "clear" poses several questions. Does "clear" mean devoid of all concentrations of gas or is there a tolerable maximum? How high above ground is the "clear" layer to extend? Is the region to remain "clear" under all plant operating loads and during winds of all possible speeds?

The answers to these questions often represent the difference between a major change in plant structure and equipment to secure an ideal condition, and a practical, acceptable compromise.

To put a quantitative label on the word "clear", it is necessary to discuss briefly the manner in which gas concentrations at the ground vary with stack and wind parameters.

Gas Concentrations at Ground Level

When gas is discharged into the air at stack top level, the wind carries it away from the stack and causes it to diffuse. Fig. 1(a) shows the ideal case of point source emission with no upward velocity, and with density equal to that of the air. The centerline of the trail is horizontal. The concentration falls off vertically and laterally away from the centerline, and axially away from the source. The boundaries of the plume form a cone whose traces on a vertical plane are shown. Point A on the ground close to the source is outside the plume. Point B lies well within the plume. When the wind speed is increased, the greater dilution causes Point B to experience a reduced concentration, as in Fig. 1(b).

When vertical momentum or buoyancy is added to the gas at the source, the centerline of the plume is displaced

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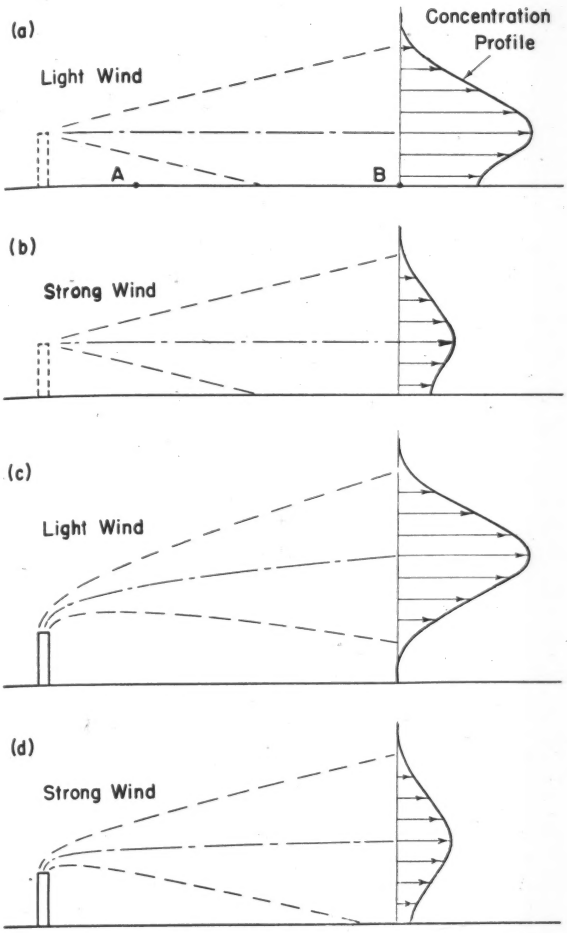

Fig. 1. Relative Effects of Plume Height and Wind Speed on Ground Concentrations.

(a) No gas ejection speed or buoyancy, light wind
(b) No gas ejection speed or buoyancy, strong wind
(c) With gas ejection speed and buoyancy, light wind
(d) With gas ejection speed and buoyancy, strong wind

upward as in Fig. 1(c). Applying the same dispersion of gas concentration about this centerline as was used in Fig. 1(a), it is seen that Point B is now free of the plume in a light wind. However, at a higher wind speed, Fig. 1(d), the centerline of the plume will have dropped, thus bringing Point B into a region of higher concentration. This is offset by greater dilution at higher speeds.

The significance of diffusion and dropping of the plume with increase in wind speed is shown in Fig. 2. The curves represent the variation of ground level concentration with wind speed as calculated with theoretical equations for plume path and diffusion[1-2] for a simple stack 100 ft. high and 20 ft. in diameter. The stack gas has a temperature of 100°F. above an ambient atmospheric temperature at 70°F. and ejects at a speed of 15 ft./sec. These values were chosen to emphasize important features rather than to represent typical power plant practice.

The negligible concentration at low wind speed is due to the steep rise of the gas plume, a condition shown in Fig. 1(c). With increasing speed the plume is deflected toward horizontal and when its lower edge begins to contact the ground the concentration rises rapidly, as shown in the curves. A maximum is reached beyond which the dilution due to increasing speed becomes the controlling factor.

Two regions of the speed range thus show possibilities of relief from contamination. Above the speed of maximum concentration, a tolerable level may eventually be reached, but the magnitude of the wind speed renders this impractical. The other region lies below the speed at which concentration shows a marked increase and is extremely important because it is characterized by little or no contamination over a range of speeds normally encountered during the year.

Critical Wind Speed, V_{cr}

The upper limit of this region of no contamination will be called the critical wind speed since a small increase in speed will cause a rapid rise in gas concentration at ground level. Sherlock[3] defines a critical wind speed which in principle appears the same as that used in this paper but is based on geometry of plume edge rather than concentration characteristics.

Whether the concentration will increase to an undesirable value depends on the situation. Gas emitted from a tall stack into an almost undisturbed air stream will diffuse in a small cone angle so that only the fringes may touch the ground. Here the critical wind speed is not significant, but this case rarely causes a pollution problem. When short stacks adjacent to or atop a large building emit gas the entire plume is brought bodily toward the ground before much diffusion can occur. If the plume touches the ground the rate of build up of concentration is extremely rapid, and the speed at touching becomes critical indeed. Industrial plants causing pollution usually exhibit the latter characteristic.

The determination of V_{cr} can be made in a wind tunnel that is not equipped for quantitative concentration sampling since it is a threshold indication. A convenient method is to use smoke to represent stack gas and a light beam-phototube combination on the floor of the tunnel at the complaint area. At very low wind speeds the plume is high off the ground. As the wind speed is increased, the plume falls until its lower edge intercepts the light beam. A microammeter in the phototube circuit indicates the loss in light intensity due to the smoke, thus establishing V_{cr}. Fig. 3 is a typical record of such a test

1. "Dust Deposition from Chimney Stacks", C. H. Besanquet, W. F. Carey, and E. M. Halton, Proceedings of the Institution of Mechanical Engineers, Vol. 162, No. 3, 1950, pp. 355-367.
2. "The Theoretical Distribution of Airborne Pollution from Factory Chimneys", O. G. Sutton, Quarterly Journal of Meteorology, Vol. 73, July-October 1947, pp. 426-436.
3. "Design of Chimneys to Control Downwash of Gases", R. H. Sherlock and E. J. Lesher, The American Society of Mechanical Engineers, Paper No. 53-A-80, 1953.

carried out to extremely high speeds to show the general similarity of the test result to the theoretical curves of Fig. 2. An essential difference in conditions is the presence of plant structure in the wind tunnel test which causes a more diffused plume.

The results shown in Fig. 3 were obtained using a single stack adjacent to a building having the shape of a rectangular prism oriented diagonally to the wind. The stack scaled 20 ft. in diameter and 100 ft. in height. The building scaled 92 ft. in height, 150 ft. in width and 215 ft. in length. The sampling distance scaled 3000 ft. downwind from the stack. The stack was operating at a scale ejection speed of 30 fps. and a simulated temperature of 100°F. above ambient.

It should be noted that the theoretical curves were calculated for point concentrations while the test points were line concentrations across the tunnel floor. However, integration of theoretical point concentrations along such a line can be shown to produce a curve similar in shape to that of Fig. 2.

Application of V_{cr}

Since variation in stack height and diameter, gas ejection speed and temperature, and obstructions to airflow in the vicinity of the point of emission strongly influence the height of the center of the plume, V_{cr} will be sensitive to the same factors. The test run which yielded the curve shown in Fig. 3 established 10 mph. as V_{cr} for that particular set of physical and operational conditions. Succeeding runs which varied only the ejection speed yielded other values of V_{cr}. These were plotted in Fig. 4 and are represented by the left hand curve. The curve defined by these test points represents the effect of plant load (ejection speed) on V_{cr}. It may be seen that increased plant load raised V_{cr} and thus was favorable for reducing pollution.

The other curves show the effect of 200° F. increase in gas temperature, and the effect of a 100 ft. stack extension above the existing 100 ft. stack. Both modifications are favorable. The horizontal displacement of the curves shows the degree of improvement at any given plant load.

Important Variables for Tunnel Tests

For a given plant in its topographical environment a number of variables affect the critical wind speed. A useful wind tunnel experiment can be made with five variables, namely, atmospheric air density, wind speed, wind direction, stack gas density and ejection speed. In a program of experiments the number is reduced to four by using the ratio of gas to air density.

Omitted from this list of variables is atmospheric turbulence. The thermally neutral airstream of the wind tunnel produces one of a range of possible turbulence conditions. Fortunately it falls between the extremes and may in some cases be an average condition. Omission of the turbulence variable is one of the factors to be taken into account in the evaluation of wind tunnel test results.

Scale Factors

The determination of V_{cr} in the wind tunnel requires that all factors which influence the plume path be properly scaled. Thus, scale factors must be used on physical size, fluid velocities and densities.

A requirement assumed in the following analysis is that the path of the gas plume in model experiments and full scale plant be geometrically similar. A logical result of

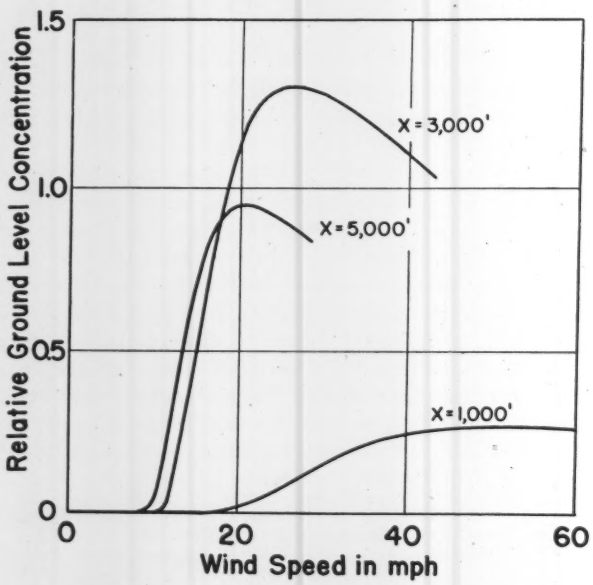

Fig. 2. Calculated Variation of Ground Concentration with Wind Speed at Three Downwind Distances. Simple 100 ft. stack with $d = 20$ ft., $V_s = 15$ fps. and $T_s = 100°F$ above ambient.

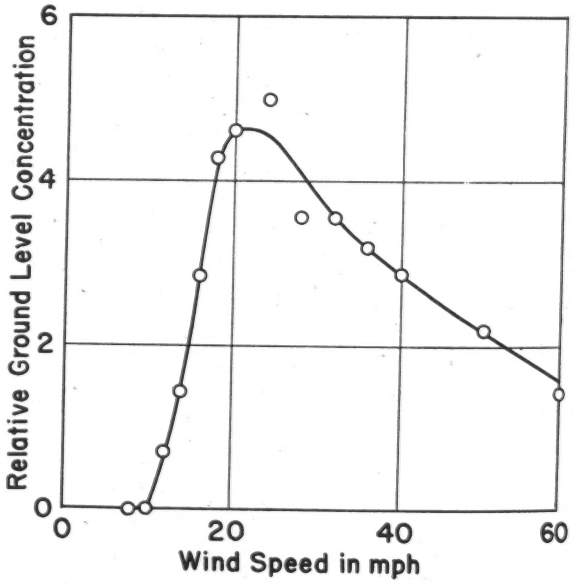

Fig. 3. Results of a Test Run on a Block Model of a Building with a Single Stack Using the Light Beam-Phototube Method. Phototube Output is Plotted as Relative Concentration vs. Full Scale Wind Speed.

this requirement is that all structures and topographical features have geometric similarity. This is achieved by scaling all linear dimensions with the same linear scale factor. Implicit in geometric similarity is that the wind direction be the same for model and full scale.

Scale factors for wind and gas variables are developed from the following equations of plume path used in the calculations for Fig. 2. They are a modified form of the equations in reference (1).

Total rise of plume above stack top (at downwind distance x) $= z_v + z_b$

Velocity rise z_v

$$\frac{z_v}{d} = \frac{z_{max}}{d}\left(\frac{1-0.8\frac{z_{max}}{d}}{\frac{x}{d}}\right) \tag{1}$$

$$\frac{z_{max}}{d} = \frac{4.23}{1+0.43\frac{V}{V_s}} - \frac{V_s}{V}\sqrt{\frac{\rho_s}{\rho}} \tag{2}$$

Buoyancy rise z_b

$$\frac{z_b}{d} = 5.01\frac{1}{\frac{V^2}{gd}}\frac{V_s}{V}\left(1-\frac{\rho_s}{\rho}\right)Z \tag{3}$$

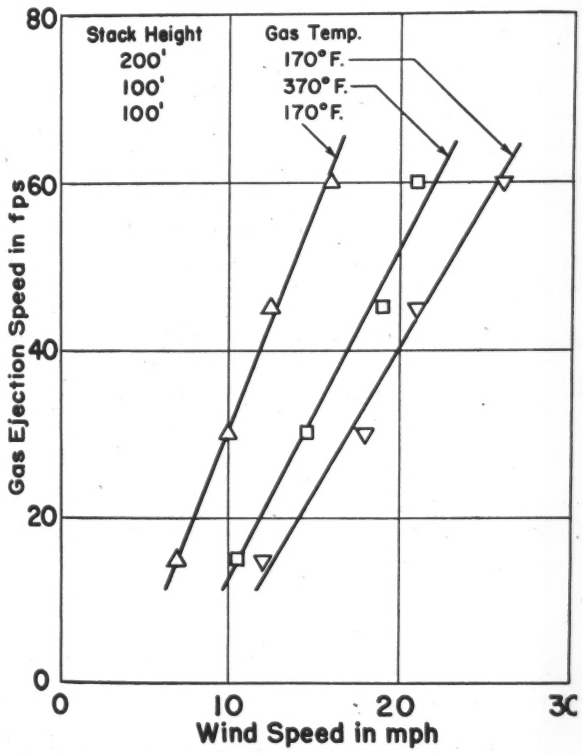

Fig. 4. Some Wind Tunnel Test Results for a Block Model of a Building with a Single Stack, Showing Variation of V_{cr} with Plant Load, Gas Temperature and Stack Height.

$Z = f(X)$ by curve in Fig. 8 reference (1)

$$X = \frac{1}{3.16}\frac{x}{d}\frac{V}{V_s}\sqrt{\frac{\rho}{\rho_s}} \tag{4}$$

where d = stack diameter
V = wind speed
ρ = air density
V_s = gas ejection speed
ρ_s = gas density
g = acceleration due to gravity

Velocity rise and buoyancy rise are functions of downwind distance and variables of velocity and density. For geometric similarity the ratios of plume dimensions to stack diameter

$$\frac{z_v}{d}, \frac{z_b}{d}, \frac{x}{d}$$

must be kept the same for model and full scale under a given set of velocity and density conditions. This is accomplished if the ratios

$$\frac{V_s}{V}, \frac{\rho_s}{\rho} \quad \text{and} \quad \frac{V^2}{dg}$$

are the same for model and full scale. The last ratio is recognized as Froudes Number. Expressed as equations relating model and full scale variables they form the following:

$$\left(\frac{\rho_s}{\rho}\right)_M = \left(\frac{\rho_s}{\rho}\right)_F \tag{5}$$

$$\left(\frac{V_s}{V}\right)_M = \left(\frac{V_s}{V}\right)_F \tag{6}$$

$$\left(\frac{V^2}{gd}\right)_M = \left(\frac{V^2}{gd}\right)_F \tag{7}$$

where the subscripts "M" and "F" refer to model and full scale, respectively. Since g is nearly constant it may be eliminated with little loss in accuracy. Equations (6) and (7) may be written in the following form

$$(V_s)_M = (V_s)_F\sqrt{\frac{d_M}{d_F}} \tag{6a}$$

$$(V)_M = (V)_F\sqrt{\frac{d_M}{d_F}} \tag{7a}$$

$\frac{d_M}{d_F}$ is the linear scale factor in terms of stack diameter. Any convenient reference dimension can be used. Equations (5), (6) and (7) or (5), (6a) and (7a) together with geometric similarity determine the test conditions.

For the special case of equal air and gas density two of the scale factors are eliminated. There is no plume rise due to buoyancy and the velocity rise equation yields the scale factor $\frac{V_s}{V}$. Thus only equation (6) need be satisfied. This results in considerable simplification of test program and equipment. The extent to which density effects can be neglected in model experiments seems an open question. It is felt that this will vary considerably

with specific cases. For hot gases omission of density characteristics is conservative and is less serious for high wind speeds.

Some mention must be made of Reynolds Number as a possible scale factor. It does not appear in the plume path equations used in the preceding development probably because they were not intended for application to stacks as small as those used in scale models. Some tunnel experiments on simple stacks have, however, shown good agreement.[6] The effect of Reynolds Number on patterns of air motion for conventional building shapes has been shown negligible in various aerodynamic studies.

Historical Development

The procedures described in this paper were developed in cooperation with the Cleveland Electric Illuminating Company during tests of the Avon Power Plant at the New York University 3½ x 7 ft. wind tunnel starting in November 1952.

Preliminary runs made according to the tunnel practice at that time showed very conservative results in that pollution was observed in the tunnel at ground level at wind speeds much lower than had been recorded in field studies during the previous year. On the supposition that lack of buoyancy was at fault, an attempt was made to simulate the true gas density by adding helium to the smoke in calculated proportions at ambient temperature. The results showed such promise that re-evaluation of the entire test procedure seemed in order. The test was discontinued while changes were completed in the tunnel structure and new instrumentation developed. Tests were resumed in March 1953 and completed in May 1953.

As discussed under Scale Factors, the addition of buoyancy introduced a scale factor on velocity which had not been necessary when only wind and gas momentum were considered. This scale factor, Froudes Number, required that all speeds be reduced according to the square root of the linear scale. Thus a linear scale factor of 1:240 as used in the Avon test required a velocity scale factor of 1:15.5. Since the range of wind speeds encountered in full size was of the order of 10 to 35 mph., the corresponding tunnel speeds were about 1 to 3 fps.

Previous experience had shown that attainment of a steady air stream below 5 fps. was very difficult and almost impossible at 1 fps. The difficulty lay in the fact that the tunnel was of the non-recirculating type, drawing air from the building and discharging it to the outside. Thermal currents and local air motions due to drafts and fans in the building were drawn into the intake and appeared in the air stream at low speeds as unwanted turbulence.

Just prior to the Avon test, the tunnel had been under reconstruction as part of a program of atmospheric turbulence studies for the Atomic Energy Commission. One phase of the program was the rebuilding and insulating of the intake end of the tunnel to remove these thermals so that tests could be performed at low speeds. The buoyancy requirement made it mandatory that this new entrance section be completed before resuming the Avon test.

By March 1953, the new intake structure had been proved successful in producing a quiet air stream at all anticipated tunnel test speeds. In addition, the light beam-phototube smoke detector had been developed to sufficient sensitivity that it could detect wisps of smoke which straggled below the main body of the plume. With these two major changes, the Avon test could now proceed.

Apparatus

The test section of the tunnel is 30 ft. long, 3½ ft. high, and 7 ft. wide. The plant model is located at the beginning of the test section, and for convenient observation of the smoke plume, one side of the entire test section is of plate glass. Wind speed is controlled by a Ward-Leonard System applied to the fan motor at the discharge end of the tunnel, and wind speed is measured with a thermopile type probe (Hastings Air Meter) over the model. For smoke generation, air metered through a Flowrator is passed through a metal chamber into which oil vapor produced by electrically heated vaporizers is admitted. Smoke density is controlled by adjustment of the oil supply to the vaporizers. Helium is also metered through a Flowrator before addition to the smoke in the tube leading to the model. For detection of pollution at ground level, the phototube was installed at a scale distance of 3000 feet from the plant facing a light source across the tunnel, the beam being approximately 20 feet above the ground.

Test Conditions

The test was run in a neutral atmosphere, i.e., temperature did not vary with height. The effects of atmospheric turbulence which are thermal in origin must therefore be kept in mind when applying test results.

The topography was reproduced in the circle of the turntable on which the model was placed, a radius of 36 in. or 720 scale feet. The upwind terrain was the flat water surface of Lake Erie. Downwind the terrain consisted of flat land. It was not considered necessary to reproduce low level irregularities since the turbulence generated by the building (177 ft. high) was so large in comparison. Fig. 5 shows the model in the tunnel.

Test Procedure

When the air flow, helium flow, and smoke density are properly adjusted, the wind is set at a speed low enough so that the smoke plume is visibly off the ground. The light meter connected to the phototube is read. The wind speed is increased in small increments and the corresponding light meter readings noted and plotted for determination of critical wind speed. It is to be noted that in this method of test, although the slope of the curve

6. "The Smokestack Problem Through Wind Tunnel Models", G. H. Strom and J. Halitsky, Paper No. 4, Report of Symposium V—Aerosols, Chemical and Radiological Laboratories, Army Chemical Center, Maryland, June 1953.

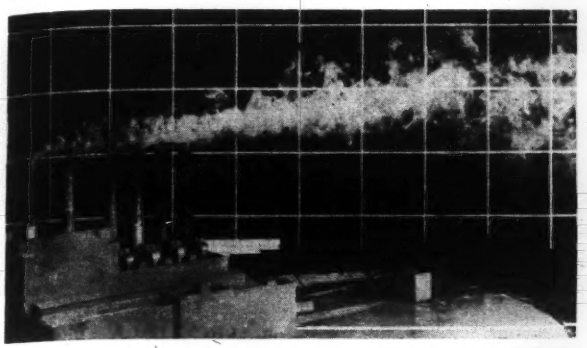

Fig. 5. Photograph of Avon Plant in Wind Tunnel with Full Boiler Load and Scale Wind Speed of 19 mph.

thus obtained will depend strongly on the density of the smoke entering the model, the zero intercept is very insensitive to density, provided that the smoke is not so dense that the particles appreciably affect the specific gravity.

Test Results

The foregoing apparatus and test procedure having been developed, the Avon Plant model was tested. Salient results are as follows:

Confirming theory and previous experience at this laboratory and elsewhere, it was demonstrated that downwash of the plume is encouraged by high wind speeds and low stack velocities.

Also confirming previous observations, wind direction is important. Wind of such direction as to be approximately 45° off the line of stacks produces downwash at considerably lower wind speed than winds from other directions.

With wind from this direction tests of the Avon Plant model indicated threshold contamination (i.e., initial deflection on the microammeter) at a wind speed of 19 miles per hour (V_{cr}). With all other wind directions higher wind speeds were required for threshold contamination.

For a given condition of wind direction and stack velocity it was demonstrated repeatedly that results (for example—the 19 mph. critical wind velocity) were easily reproducible.

The 19 mph. critical wind speed having been established, plant improvements were applied to the model and the tests repeated. Benefit of an improvement was evaluated by its effect in increasing the wind speed necessary to produce downwash.

It was possible to try, and to evaluate the effectiveness on Avon Plant of a number of the measures frequently considered for downwash abatement such as higher stacks, nozzles, guide vanes on the stacks, dilution of stack gas with air for greater velocity, streamlining of the building, and even vanes for correcting unfavorable wind patterns caused by the structure. With the wind tunnel each of these measures was evaluated in terms of resulting increased critical wind speed.

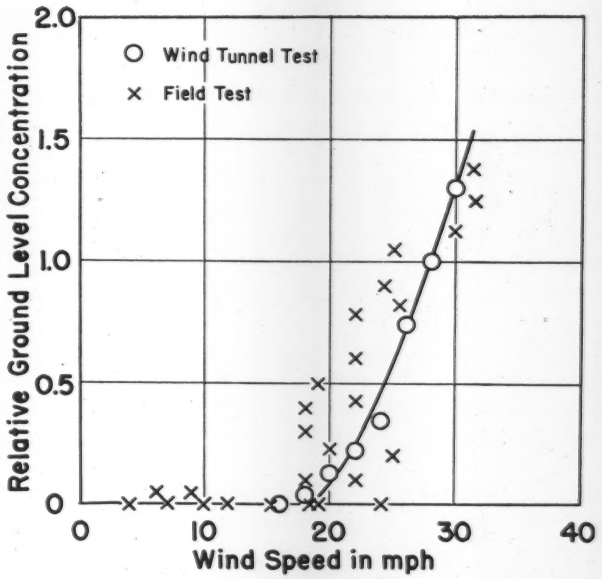

Fig. 6. Comparison of Avon Plant Field and Wind Tunnel Test Results at One Downwind Location for the Wind Direction of Fig. 5.

Data so obtained, applied to U.S. Weather Bureau data for the locality on duration of winds of various speeds for each direction, permitted the calculation of the reduction in hours of downwash per year which may be accomplished by use of a corrective measure under consideration.

Accuracy of Wind Tunnel Experiments

The ever-present and most important question relating to tests of this nature is "How do the wind tunnel results compare with the behavior of the prototype plant?"

Prior to the undertaking of the wind tunnel tests of Avon Plant, the Cleveland Electric Illuminating Company had made a broad survey of conditions in the vicinity of the plant in Avon Lake Village. Some twenty sampling station locations were established in various directions and ranging up to 1½ miles from the plant and many hundreds of SO_2 analyses of the air were made at these locations. The analyses were correlated with wind direction, wind velocity and a number of other factors. Samples were initially taken daily for a period of 8 months and during the past 2½ years have been taken during critical winds. From the data for the sampling station located close to the equivalent light beam-phototube position in the tunnel, points were selected for plotting Fig. 6. The complete records for the station show readings for all wind directions but only those were taken which brought the plume over the station.

The wind tunnel test points are based on readings of phototube output found by the procedure described earlier. As there was no calibration made of the relation between instrument readings and smoke concentration, the instrument readings were arbitrarily multiplied by a factor which gave the wind tunnel curve approximately the same slope as the field test points. To this extent

the correlation is indefinite but the critical wind speed is not affected.

The wind tunnel curve is interpreted as giving a critical wind speed of approximately 19 mph. The full scale points show a dispersion as is expected, considering the range of atmospheric turbulence conditions, but a reasonable interpretation yields approximately the same critical wind speed as the wind tunnel test. Field tests for other wind directions did not encounter sufficiently high wind speeds to give concentrations significant for correlation purposes.

When evaluating wind tunnel results, some allowance must be made for the lack of perfect correspondence with full scale characteristics whether due to experimental errors, atmospheric turbulence or fundamental features of wind tunnel experiments. Use of the critical wind speed has an inherent margin of safety, since some concentration can be tolerated and this will occur at speeds higher than critical. The phototube method of detecting the presence of the lower edge of the plume can be adjusted to provide a margin of safety. At best the light beam must be located a small distance above the floor and will therefore register the plume before it actually contacts the ground. Additional margin can be obtained by raising the beam to a higher level.

Whether the favorable correlation in Fig. 6 will be found for experiments on other power plants is open to question. Further field studies for specific cases are needed to place wind tunnel experimentation on a firmer basis and special emphasis should be placed on those having important topographical influences.[4]

Development of wind tunnel apparatus for precise control and measurement of gas concentrations will yield another important form of data and facilitate the correlation with field experiments but will not change the fundamental nature of the experiments.

Simulation of atmospheric turbulence over a range of stability conditions will add a new variable serving to extend the range of test conditions. A project under the sponsorship of the Atomic Energy Commission at the New York University wind tunnel is directed to the development of equipment and techniques for this purpose. Favorable results of a qualitative nature were found in the earlier stages of the project[5] but close control of turbulence characteristics has required extensive development of special equipment. The equipment phase is nearing completion and a program of experiments, scheduled for the near future, will give a basis for evaluating the possibilities of reproducing atmospheric turbulence in wind tunnel experiments.

While experiments on power plant models have given useful results in the past, further development of this field of investigation may yield a more effective tool for the solution of atmospheric pollution problems. The rate of development will depend on the interest and demands of potential users.

Acknowledgments

Grateful acknowledgement is made to the Cleveland Electric Illuminating Company for their support in development of instrumentation used in the Avon tests, and for permission to use field and test data in this paper.

Our warm appreciation is expressed to Mr. F. J. Leonhard, General Supervising Engineer, Production Engineering - Planning, of that Company, whose interest and participation in the tests contributed a great deal to preparation of this paper.

We wish to give due recognition to the Consolidated Edison Company of New York and to the U.S. Atomic Energy Commission who shared the financial burden in developing the tunnel. Much of our success is due to the encouragment and advice given so generously by Mr. Ward F. Davidson, Research Engineer, of Consolidated Edison in the earlier stages of tunnel development.

4. "Topographical Influences on Dispersal of Stack Gases", G. H. Strom and J. Halitsky, Combustion, Vol. 24, No. 12, June 1953, pp. 40-43.

5. "Wind Tunnel Techniques Used to Study Influence of Building Configuration on Stack Gas Dispersal", G. H. Strom, American Industrial Hygiene Association Quarterly, Vol. 13, No. 2, June 1952, pp. 76-80.

Discussion of "TVA Air Pollution Studies"

(Continued from page 12)

is emphasized by the fact that it occurs during more than about 50 per cent of annual hours. Further, both wind tunnel studies and field observations emphasize that once the plume from the stack becomes trapped in the turbulence created by the station, it will not only be brought to ground or roof top levels, but it will remain trapped for considerable downwind distances.

There is another area where the results presented in the paper are quite different from those observed in New York. The author, in his discussion of the data presented in Figure 3 and Table 2, suggests that the buoyancy effect of the hot effluent gases has been under estimated by most other investigators. For New York, at least, this would not seem to be supported by other data. The data of Figure 3 indicate as much as a 5-fold increase in effective stack height for wind speeds of about 8 mph. However, for New York this apparent bonus in effective stack height largely disappears when it is noted that winds less than 8 mph. at the top of the stack occur during only about 10 per cent of the time. During 90 per cent of the time the increase in effective stack height due to buoyancy would be less than 3-fold. Increasing the temperature of the effluent gases would, therefore, seem to be an expensive way of solving the diffusion problem. Studies which were reported in 1951 at the Roanoke meeting of the Air Pollution Control Association, indicated that a better solution was based on the use of nozzles at the top of the stack to obtain higher, and controlled, exit gas velocities.

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Detection of Smog Forming Hydrocarbons in Automobile Exhaust Gases Using Plants As Indicators

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The important contribution of hydrocarbons to the Los Angeles smog has been described by the Air Pollution Control District, Haagen-Smit, and other workers in this field[6-7-8]. Certain known effects of the polluted air, such as damage to vegetation and irritation to the eyes have been related to oxidation reactions occurring in the atmosphere involving olefins and branched chain hydrocarbons[4-5-6].

Preliminary evaluations of the sources contributing hydrocarbons to smog strongly indicated the need for studies of the exhaust fumes emitted by automobiles. Quantitative values on the hydrocarbon content of exhaust gases have been reported and, qualitatively, mass spectrometer analyses have shown the presence of unsaturated hydrocarbons in the 4, 5, and 6 carbon atom range[14]. Each of these hydrocarbons has been shown to produce the effects of smog when individually oxidized by ozone or by oxides of nitrogen in the presence of sunlight.

Exact identification of the gases and vapors that are present in exhaust fumes is extremely difficult. In addition, there was no evidence to indicate that these hydrocarbons, mixed with other gases in the automobile exhaust, could still produce smog-like effects. It, therefore, became necessary to duplicate the atmospheric reaction as closely as possible in a test chamber and to use smog-sensitive plants as a means for identifying these hydrocarbons responsible for plant damage[6-9-15]. Since the products of oxidized gasoline vapors had been used in the initial work of determining which hydrocarbons were factors in plant damage[6], gasoline vapor was used as a standard for comparison of the effects created by auto exhaust.

Apparatus and Procedure

An 11,000 liter Plexiglas chamber was used for the dual purpose of mixing the gases and for fumigating the test plants Fig. 1. The air rate through this chamber was 650 liters per minute, corresponding to a 17 minute turnover. The incoming air passed through an activated carbon filter to remove gaseous contaminants. It then passed through an evaporative type cooler to afford some control of temperature and humidity. Sunlight was used as the source of illumination.

The fumigants were introduced into the chamber through separate tubes with outlets six inches apart Fig. 2. A fan, placed beneath the outlets, directed a current of air vertically upward to insure immediate and complete dispersion of the fumigants. Mixing in this manner at concentrations approaching those found in the atmosphere avoided the formation of a dense aerosol such as results from mixing of ozone and unsaturated hydrocarbons at high concentrations. Gasoline vapors were introduced by passing nitrogen at a constant rate through a micro-impinger containing gasoline.

Automobile exhaust fumes were introduced directly from the exhaust pipe through a Sprague dry test meter into the chamber. After initially adjusting the flow rate, the test meter was removed to prevent clogging due to the condensation of moisture. The flow rate of the ex-

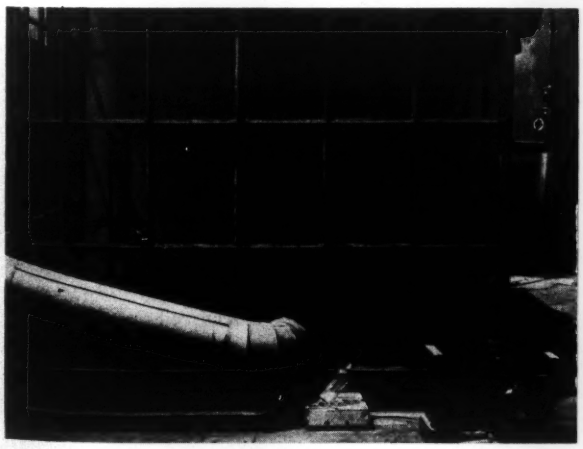

Fig. 1. Plexiglas Chamber.

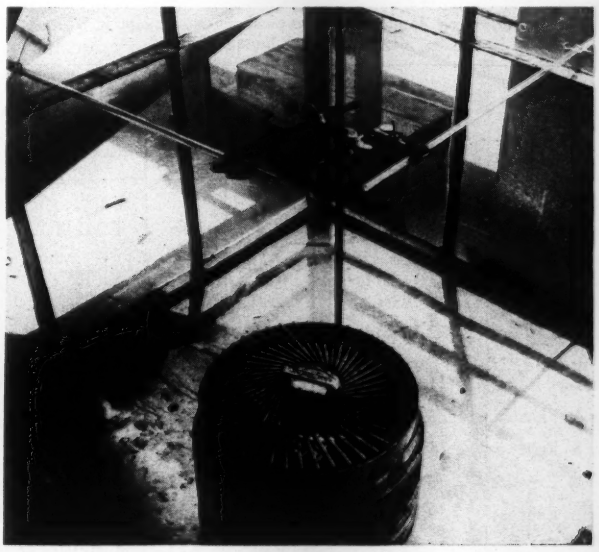

Fig. 2. Intake and Fan Arrangement.

haust was controlled through the use of a bleeder valve in the input line and a small water trap was used to remove excess water vapor.

Due to the difficulty involved in conducting a fumigation with exhaust gases from all four driving conditions, (idling, cruising, accelerating and decelerating) only idling fumes were employed. This was considered to be valid since analyses show the hydrocarbon concentration under idling conditions to be an approximate average of all four conditions[7-14]. The exhaust gases used in this test were from a 1950 International six cylinder truck. One month prior to the tests, the carburetor was cleaned and adjusted, which accounts for a lower hydrocarbon concentration than was shown in reports on idling by others[7-14]. The gasoline used in the truck was a premium grade containing 20 per cent unsaturates.

For the fumigations with gasoline and ozone, oxides of nitrogen were added in a concentration comparable to that found in the diluted exhaust gases. This was done to simulate more closely atmospheric conditions since these oxides act as oxidants or catalysts in the reaction. A hypodermic syringe dispenser devised by Roth[16] was used to introduce the gaseous oxides of nitrogen into the chamber. The outlet of the syringe was located over the fan six inches from each of the other gaseous outlets. Gasoline used for fumigation was a non-leaded regular grade containing 15 percent unsaturates.

Test plants were grown in the Earhart Plant Research Laboratory at the California Institute of Technology[19]. Plants are grown there in a smog-free atmosphere under carefully controlled conditions of humidity, temperature and nutrition, thus providing maximum uniformity of test material. Oats were ready for use in 10 days. The other plants were used at about the age of 20 days.

Ozone was manufactured from pure oxygen in a Berthelot tube capable of producing 6 per cent ozone at an oxygen rate of 60 milliliters per minute and at a potential of 7,500 volts. The ozone concentration in the chamber was controlled by varying the flow rate of oxygen through the ozonizer. A calcium chloride tube was placed ahead of the ozonizer to insure the absence of water in the ozonizer.

TABLE I

SUMMARY OF RESULTS

S = spinach, B = sugar beet, O = oat, A = alfalfa, E = endive; T = typical smog damage, t = typical smog damage in a lesser degree, 0 = no damage

FUMIGANTS	CONCENTRATION			PLANT DAMAGE				
	Hydrocarbons as measured by Infrared in mg./liter	Utilized O_3 in p.p.m.	NO_2 in p.p.m	S	E	B	O	A
No_2, Ozone & gasoline	5.3×10^{-2}	0.23	0.86	T	T	T	T	T
No_2, Ozone & gasoline	8.0×10^{-2}	0.21	0.41	T	T	t	T	T
No_2, Ozone & gasoline	2.5×10^{-2}	0.04	0.36	t	t	0	t	0
No_2, Ozone & gasoline	1.5×10^{-2}	0.11	0.23	t	0	0	0	0
Ozone & Exhaust	3.7×10^{-2}	0.19	0.20	T	T	T	T	T
Ozone & Exhaust	5.2×10^{-2}	0.28	0.17	T	T	T	T	t
Ozone & Exhaust	3.6×10^{-2}	0.17	0.23	T	T	t	T	t
Ozone & Exhaust	2.7×10^{-2}	0.20	0.25	0	t	0	t	0
Ozone & Exhaust	1.9×10^{-2}	0.18	0.23	t	0	0	0	0

Sampling and Analytical Procedures

Ozone was admitted to the chamber until a concentration of 0.33 p.p.m. was reached. During the fumigation the concentrations in the chamber of hydrocarbons, aldehydes, formic acid and residual ozone were measured.

Ozone was measured by the rubber cracking method[1-8]. This test involves drawing the air at a given rate through a tube containing a folded standard strip of rubber and determining the length of time for the initial cracking.

Hydrocarbons were collected by freeze-out in a modified Shepherd trap using liquid oxygen as the refrigerant[12-17-18]. The sample rate was one liter per minute. Concentrations were determined by means of a Beckman infrared spectrophotometer using the method described by Mader et al[12]. Gasoline hydrocarbon values were reported in milligrams per liter of gaseous sample collected, based upon the calibrated extinction coefficient for gasoline vapor. No calibration has been performed with car exhaust gases. The hydrocarbon concentration of these gases was based upon a calculated coefficient using the relative concentrations and the known extinction coefficients of the individual hydrocarbons present in the exhaust as measured by Magill[14]. Methane, ethylene, and 50 per cent of the acetylene present were assumed to escape collection in the freeze-out trap.

Aldehydes were absorbed in 1 per cent sodium bisulfite in three micro-impingers at a rate of 0.1 cubic foot per minute. The bisulfite addition products were isolated and then titrated with iodine[2-10]. The results were calculated as formaldehyde.

Formic acid was collected in sodium hydroxide in two micro-impingers. The formate was hydrolized and reduced to formaldehyde which forms a colored complex with chromotropic acid. The intensity of color was measured with a Beckman ultraviolet spectophotometer[3-11].

Typical damage, as used here, is that described in the literature and which in addition exhibits a definite pattern of injury dependent on the maturity of the leaf[6-9].

Experimental Results

The minimum concentrations in the car exhaust fumigations in which typical damage occurred to all five plants were 0.19 p.p.m. of ozone consumed and 3.7×10^{-2} milligrams per liter of exhaust hydrocarbons. The corresponding minima for fumigations with gasoline were 0.23 p.p.m. of ozone and 5.3×10^{-2} milligrams per liter of gasoline hydrocarbons.

TABLE II
RESULTS WITH GASOLINE

S = spinach, B = sugar beet, O = oat, A = alfalfa, E = endive;
T = typical smog damage, t = typical smog damage in a lesser degree, 0 = no damage

Utilized p.p.m. O_3	Measured Hydrocarbon *mg/l.*	NO_2 in p.p.m.	HCOOH in p.p.m.	Aldehydes in p.p.m.	Temperature °F.	Relative Humidity %	PLANT DAMAGE				
							S	B	O	A	E
0.23	5.3×10^{-2}	0.86	0.67	1.50	83	54	T	T	T	T	T
0.19	6.9×10^{-2}	0.00	*	1.85	87	53	T	T	t	t	t
0.21	8.0×10^{-2}	0.41	0.45	1.64	83	56	T	t	T	T	T
0.05	1.9×10^{-2}	0.33	0.25	0.96	92	41	t	t	0	0	0
0.04	2.5×10^{-2}	0.36	0.13	0.51	86	45	t	0	t	0	t
0.25	10.2×10^{-2}	0.00	*	1.99	81	54	t	0	0	0	0
0.11	1.5×10^{-2}	0.23	0.10	0.35	69	71	t	0	0	0	0
0.08	1.8×10^{-2}	0.26	0.15	0.42	88	43	0	t	t	t	t

*Not measured

Examination of the results (Table I) indicates that hydrocarbons from automobile exhaust are equally as effective as gasoline vapors in the production of damage to all five plants.

It is probable that damage may be obtained at lower hydrocarbon concentrations by variations in fumigation techniques. Further studies along this line are being carried out.

It was observed during these tests that almost twice as much ozone reacted with the exhaust as with gasoline. This may have been due to the higher olefin content of the former. Temperature, light intensity and relative humidity within the limits encountered in this work appeared to have little effect upon the fumigation results (Tables II and III). The inclusion of oxides of nitrogen in the fumigations with gasoline and ozone resulted in a higher degree of damage.

Formic acid and aldehydes were measured primarily as an indication of the oxidation reaction.

It was observed that mixing exhaust gases with ozone resulted in the production of a definite visible aerosol[13].

Summary

Crop damaging hydrocarbons which produce the same effect as smog are present in automobile exhaust gases. In the presence of ozone, auto exhaust fumes diluted 1:116 produced typical damage to the five smog indicator plants (spinach, oat, sugar beet, endive, and alfalfa). Comparison with gasoline indicated that hydrocarbons from automobile exhaust gases are at least equally as effective as gasoline in producing typical smog damage on the five indicator plants.

Because of the significance of the findings expressed in this report, the Los Angeles County Air Pollution Control District is continuing investigations to determine

TABLE III
RESULTS WITH EXHAUST GASES

S = spinach, B = sugar beet, O = oat, A = alfalfa, E = endive;
T = typical smog damage, t = typical smog damage in a lesser degree, 0 = no damage

Utilized p.p.m. O_3	Measured Hydrocarbon *mg/l.*	NO_2 in p.p.m.	HCOOH in p.p.m.	Aldehydes in p.p.m.	Exhaust Dilution	Temperature °F.	Relative Humidity %	PLANT DAMAGE				
								S	B	O	A	E
0.19	3.7×10^{-2}	0.20	0.41	1.67	1:116	83	51	T	T	T	T	T
0.28	5.2×10^{-2}	0.17	0.23	1.18	1:116	71	68	T	T	T	t	T
0.26	5.8×10^{-2}	0.32	0.24	1.15	1:116	83	53	T	T	T	T	t
0.33	20.0×10^{-2}	0.71	*	1.04	1:29	80	64	T	T	T	T	T
0.33	22.2×10^{-2}	1.81	*	2.69	1:29	82	58	T	T	T	T	T
0.17	3.6×10^{-2}	0.23	0.27	1.02	1:116	80	45	T	t	T	t	T
0.33	11.7×10^{-2}	0.32	0.33	1.40	1:58	83	58	T	0	t	t	T
0.33	9.7×10^{-2}	0.20	0.20	2.15	1:58	87	52	T	t	t	t	0
0.20	2.7×10^{-2}	0.25	0.17	0.24	1:232	83	59	0	0	t	0	t
0.18	1.9×10^{-2}	0.23	0.07	0.22	1:232	79	60	t	0	0	0	0

*Not measured

the impact of the total contribution of exhaust gases to the air pollution effects found in the community.

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(*Continued from page 6*)

Appraisal of Odor Problems

measures temperature rise and provides for odor sampling[14].

When a catalyst is used to aid combustion, the presence or absence of catalyst poisons in the odorous gas will be critical in determining maintenance costs. Analysis for catalyst poisons may be carried out indirectly by an exhaustive life test on the catalyst using one of the instruments described above. In some cases, the presence of flagrant poisons, such as metallic vapors, may be detected by conventional chemical methods of analysis.

Organoleptic testing for effectiveness of odor elimination is particularly important for combustion methods. A partial oxidation (e.g. aldehydes to acids) may change odor quality without reducing intensity or objectionable character. In some cases final oxidation products are odorous, although this is not a frequent problem.

Scrubbing. The prediction of the efficacy and maintenance of a scrubbing operation, assuming efficient gas-to-liquid contact, can be made by conventional chemical means. Scrubbing is very easily conducted on a laboratory scale, and the rate at which the scrubbed liquid becomes saturated or exhausted can be readily determined. When a chemical reaction is involved (e.g. neutralization or oxidation) chemical analysis alone will predict material costs. When physical solution and entrainment contribute to odor control, some form of organoleptic tests to predict effectiveness will be advisable.

The factor of gas-to-liquid contact efficiency is critical in the application of scrubbing equipment. This depends to such an extent on equipment design that it is not easy to predict from laboratory tests. This is in sharp contrast to adsorption methods, for example, where the critical factors of particle granulation and bed depth can easily be reproduced and tested. Laboratory absorbers bear little resemblance to the design of commercial scrubbers. The performance of the latter must be predicted on the basis of engineering principles and field experience.

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Development of A System For Predicting Dispersion From Stacks

By L. L. Falk, W. R. Chalker, J. A. Greene, Engineering Dept.; C. B. Cave, C. W. Thorngate, Explosives Dept.; E. I. du Pont de Nemours & Company, Inc.,

It is well known that dispersion of stack effluents is markedly affected by such weather factors as wind speed and atmospheric turbulence. Several equations have been developed that relate these factors to stack height, rate of emission of material from the stack and ground-level concentration downwind from the stack. The best known examples of these equations are those developed by Bosanquet and Pearson [1] and Sutton[2]. In these formulas, atmospheric turbulence is introduced through the use of diffusion coefficients p and q in the case of Bosanquet and Pearson and C_y, C_z and n in the work of Sutton. Evaluation of these diffusion coefficients for a given weather situation usually involves expensive equipment and long tedious calculations. Usual practice in most air pollution applications involves assumptions of average values of the turbulence coefficients.

The experimental work described in this publication indicates that:

1. Turbulence coefficients can be determined with relatively simple wind instruments;
2. The dispersion pattern from a given stack can be rapidly determined from these wind measurements;
3. A reasonable degree of accuracy can be expected in computations of the ground-level concentration calculated for a given stack.

Field Method For Studying Dispersion

Several field techniques have been developed for studying atmospheric dispersion turbulence: e.g., scattering of balloons, explosion of smoke bombs, heat or moisture transfer, etc. When applied to dispersion from stacks, these approaches can be considered as indirect. In the present work, a method was used that gave dispersion data directly.

The method selected was a tracer method involving release of finely divided fluorescent particles that could be collected downwind and counted under ultraviolet light illumination. Advantages of this method include (a) direct dispersion measurement, (b) previous development of the technique[3], (c) simplicity, (d) ease of identification of the dispersed particles, (e) extreme low concentrations of tracer that can be detected, (f) applicability of the results to both gaseous and fine particle dispersion, (g) need for such low atmospheric concentrations of tracer that odor and toxic problems are eliminated, and (h) absence of background interference as exists in using radioactive tracers.

a. *Fluorescent Tracer*

The tracer used was zinc cadmium sulfide, a yellow pigment of density 4.3 that fluoresces at 3650° Angstrom with a bright yellow greenish color. It is manufactured by the New Jersey Zinc Sales Company under the trade name "Horsehead Pigment 2266".

The frequency distribution of particle size of this pigment is given in Figure 1 and is based on the sizing of 18,000 particles. The median diameter was about 1 micron and the mean mass diameter was 2.35 microns. A particle of mass mean diameter would have a weight equal to the average weight of all the particles. Thus, each gram of pigment discharged averaged about 3.5×10^{10} separate particles. These particles were easily distinguished from naturally occurring particles in the air. Statistically significant concentrations as low as 3 to 4 particles per cu. ft. of air were detectable.

b. *Pigment Dispenser*

A dispenser was constructed to convert bulk pigment into a cloud of individual particles and discharge it to the atmosphere at a known and uniform rate. Figure 2 shows the assembled dispenser with the following parts in ascending order: blower mounted on legs, feeder wheel and

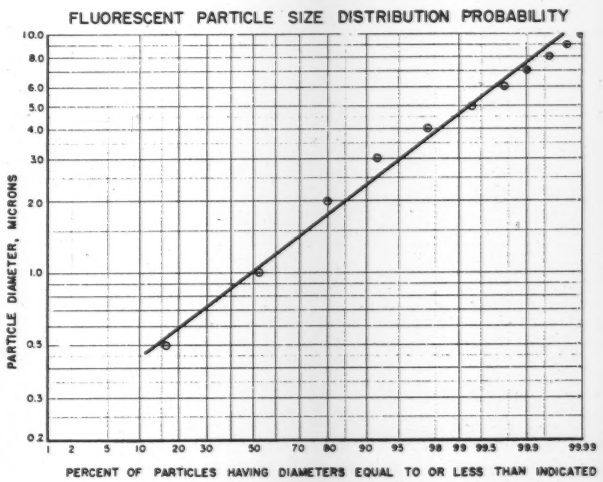

Fig. 1. Fluorescent Particle Size Distribution Probability.

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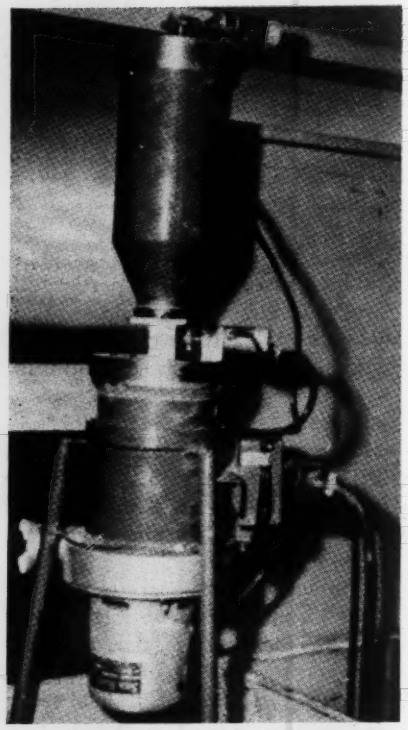

Fig. 2. Assembled Dispenser On Top Of Fire Tower.

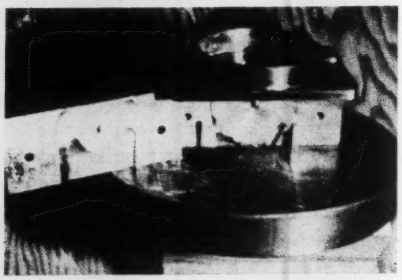

Fig. 3. Side View of Opened Feeder Wheel Housing.

Fig. 4. Drum Sampler Assembly, Generator, Control Box, Sampler Head On Post.

motor, pigment hopper and hopper cap with an agitator motor. Bulk pigment was placed in the hopper and the entire assembly of hopper cap, pigment hopper and feeder wheel-motor was weighed on a 20 kg. balance. The difference in weight before and after a test gave the total quantity of pigment discharged during the test. The hopper agitator prevented pigment from holding up in the hopper and insured a relatively uniform flow from the feeder wheel. Figure 3 shows the feeder wheel housing with one side removed to show the wheel .The teeth of the rotating wheel delivered pigment from the hopper (above) to the blower (below). A scraper spring rode up and down in the feeder wheel teeth to remove pigment delivered to the blower side of the feeder wheel housing. Pigment was directed through a funnelling cone into the blades of the blower. Air entered the blower through an outer annular space.

During most of the tests, pigment was discharged at rates of 1 to 10 grams/min. (3.5×10^{10} to 3.5×10^{11} particles).

c. *Fluorescent Particle Samplers*

Two types of equipment were used to sample fluorescent particles downwind from the source. Drum or tape samplers measured the variation of particle concentration with time. Filter samplers measured the total dosage of particles. Dosage is the integral of the product of concentration and time for the sampling period.

An assembled drum sampler is shown in Figure 4. It consisted of a motor-generator power supply, a control box with a vacuum pump and electrical equipment for automatic control of the sampler, and a sampler head. In the head is a drum rotated to receive the sampled particles on a strip of cellophane tape. The sampler head is shown mounted on a 5 ft. post.

The sampler head with drum removed is shown in Figure 5. The covered part to the rear contains the gears and motor for turning the drum and the limit switch for stopping rotation after one revolution. The rotameter for measuring the air sampling rate is mounted on top. In operation, the vacuum pump drew air through a slot in a plastic nozzle mounted about 0.01 to 0.015 in. above the cellophane tape. Particles in the air were impinged on a strip of ¾ in. No. 666 Scotch Brand cellophane tape, adhesive coated on both sides, mounted on the periphery of the drum. Air was sampled at about 18 to 20 liters per minute.

In the filter samplers, air was drawn through a 1 in. disc of hydrosol type, grid marked Millipore filter (manufactured by the Lovell Chemical Company, Watertown, Massachusetts). Figure 6 shows the filter holder assembled and Figure 7 shows it disassembled into three parts; filter disc, body of the filter holder with stainless steel screen backing, and circular top piece to hold the filter against the backing. Spring clips held the parts together. Air filtration rates for these filters were approximately 1 to 3 liters per minute.

Equipment used to draw air through the filters is shown in Figure 8. The small 6 volt motor with an attached pump and oil filter was operated by two motorcycle batteries. Each such pump assembly was calibrated for flow rate from time to time. These pumps could be operated for 5 to 6 hours without appreciable change in sampling flow due to battery discharge. Figure 9 shows the filter sampler assembled in the field. The filter in use is at the top end of a 5 ft. pole attached to a hose, that leads to the suction pump. The pole is so constructed that it can be collapsed to half its height and the entire assembly picked up and transported in a truck or other vehicle. Twenty-five such samplers were used in these tests.

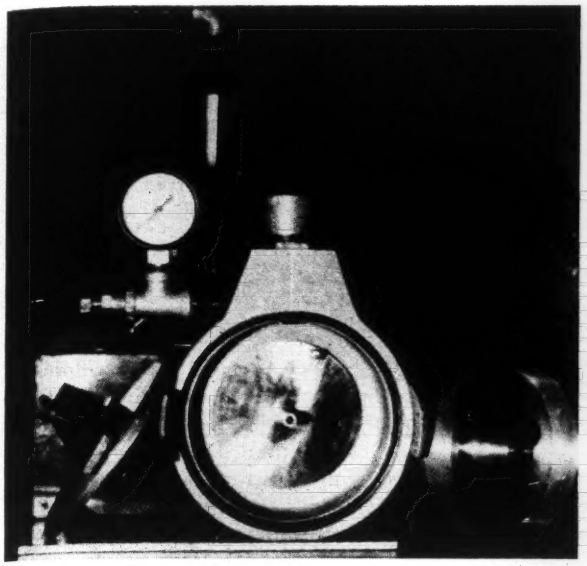

Fig. 5. Sampler Head With Drum Removed.

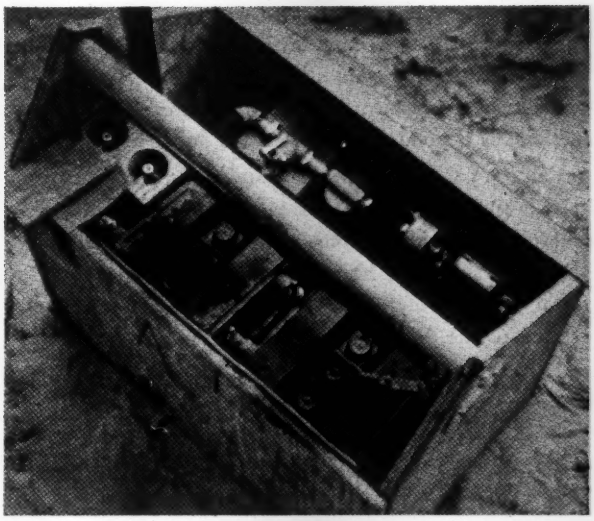

Fig. 8. Details of Advanced Filter Sampler Showing Gast Pump, Batteries and Filter Holders In Storage Slots.

Fig. 6. Filter Holder Assembled.

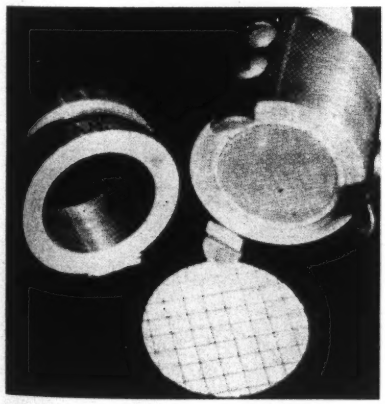

Fig. 7. Filter Holder Apart, With Millipore Filter Disk.

d. *Auxiliary Field Equipment*

A 100 ft. fire tower served as a stack or elevated source for pigment emission. Wind speed and velocity were recorded with a 3 cup anemometer and wind vane (Instrument Corporation, Baltimore, Maryland) installed 8 ft. above the top of the fire tower. Detailed wind data were obtained by operating the recorder at a rate of 3 in./min. The variation of atmospheric temperature to height above the ground was measured with a U.S. Navy AN/UMQ-3 Wiresonde. The sensory part of this instrument was raised by means of a Seyfang S-400 blimp balloon. Measurements were generally made up to a height of 400 ft.

e. *Procedure for Typical Field Experiment*

Depending upon the wind direction and the estimated degree of atmospheric turbulence, samplers were located up to 1 mile from the tower so that as complete a coverage as possible of the entire downwind dispersion pattern was obtained with the number of samplers available. Fluorescent pigment was generally dispensed for a period of ¾ to 1 hour. When conditions were favorable, it was possible to carry out up to three such tests before equipment had to be returned to the laboratory for battery recharging and reloading of the samplers.

In the laboratory, particles on the Millipore filters and drum sampler tapes were counted at a magnification of 100. Standard statistical techniques were employed to determine the number of particles to count on a given filter to obtain a reliability of 90% for a mean value of the density of all particles on the entire filter.

Lowry's method[4] for the variability of wind speed and direction involves calculation of the standard deviation of the wind speed or the wind direction measured at 10-second intervals for 10 minute periods. Three such 10 minute intervals were selected for each field experiment. The mean wind speed and direction for the entire period of the test were also determined.

Analysis of Data

a. *Analysis for Dispersion Coefficients*

One approach to the analysis of individual field experiments was com-

4. Lowry, P. H., "Microclimate Factors in Smoke Pollution from Tall Stacks," *Meteorological Monographs*, 1, 4, 24 (Nov. 1951).

putation of the dispersion coefficients to fit a reasonable equation to observe data. Several graphical techniques were developed for computing the Bosanquet and Pearson diffusion coefficients, p and q. A description of these methods is beyond the scope of this paper.

Values of p and q obtained under a variety of atmospheric turbulence conditions were found to be related to wind variability functions. The standard deviation of the wind speed at 10 second intervals, σ_{us} about the mean wind speed, $\bar{u}$, for 10 minutes, was found to be related to the diffusion coefficient, p, by:

$$p = 0.57 \frac{\sigma_{us}}{\bar{u}} \quad (1)$$

This equation is plotted in Figure 10.

If σ_z (measured in degrees) is the standard deviation of the wind direction at 10 second intervals about the mean direction for 10 minutes, the relation of this to the horizontal diffusion coefficient, q, is given in Figure 11. The straight line that best fits the data is represented by the equation

$$q = 0.048 + 0.015\ \sigma_z \quad (2)$$

σ_x is measured in degrees. $z = \theta S$.

b. *Dimensionless Analysis of Dispersion*

Dimensionless analysis affords another method for reducing all field experiments to a common basis for comparison. Differences in pigment emission rate and meteorological conditions are thus eliminated. Observed data can also be compared with existing theoretical equations by this method.

The following dimensionless functions are illustrated in Figure 12.

If x is the distance measured downwind along the axis of the dispersion cloud, and x_m is the distance directly downwind along the same axis to the point where the ground level concentration is a maximum, then the value R is defined as:

$$R = \frac{x}{x_m} \quad (3)$$

Fig. 9. Advanced Design of Filter Sampler Assembled in Field.

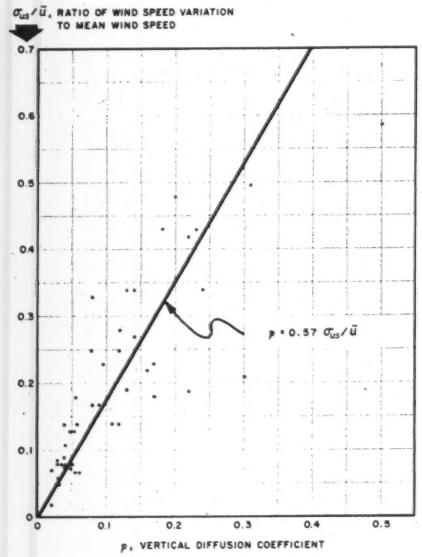

Fig. 10. Relation p and $\frac{\sigma_{us}}{u}$

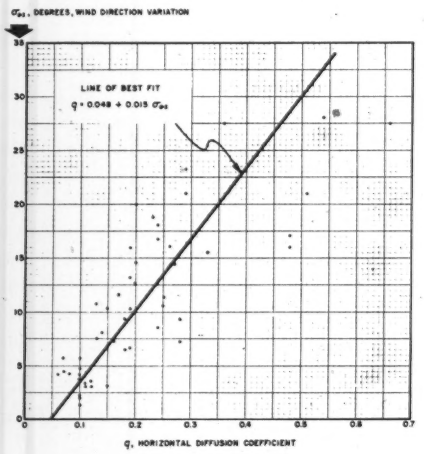

Fig. 11. Relation of q *and* σ_z. $z = \theta S$

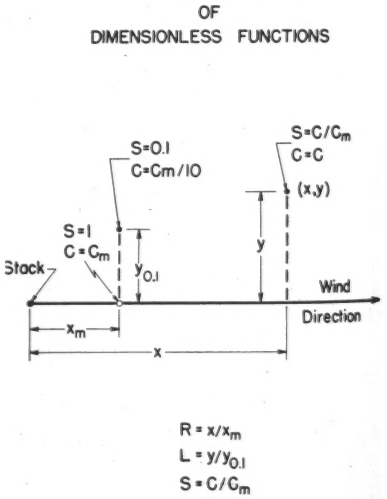

Fig. 12. Diagram Definition of Dimensionless Functions.

Similarly, if y is the distance measured crosswind or perpendicular to the axis directly down-wind from the source of $y_{0.1}$ is the crosswind distance measured at the point x_m to the point where the ground-level concentration is 1/10 the maximum concentration at x_m, then L is defined as:

$$L = \frac{y}{y_{0.1}} \tag{4}$$

Finally, if C_m is the average ground level concentration measured at the point x_m, and C is the average ground level concentration measured at the point x, y, then S is defined as:

$$S = \frac{C}{C_m} \tag{5}$$

The Bosanquet and Pearson equation is:

$$C = \frac{M}{\sqrt{2\pi\, pqux^2}}\, e^{\left(-\frac{h}{px} - \frac{y^2}{2q^2x^2}\right)} \tag{6}$$

Where u is wind speed, h is stack height, x and y are downwind and crosswind distances, M is emission rate of material from the stack and p and q are turbulence coefficients. It can be shown that the Bosanquet and Pearson equation can be expressed in the following form:

$$S = \frac{1}{R^2}\, e^{\left(2 - \frac{2}{R} - \frac{L^2}{R^2 \log e}\right)} \tag{7}$$

Note that all quantities in this equation are completely dimensionless. Sutton's equation can be expressed in a similar form except that his index n is introduced.

The significance of these questions is this:

Regardless of stack height or turbulence, when stack dispersion according to Bosanquet and Pearson or Sutton is expressed in dimensionless form, the shape of the dispersion pattern will be the same. The dimensionless plot of the Bosanquet and Pearson equation is shown in Figure 13.

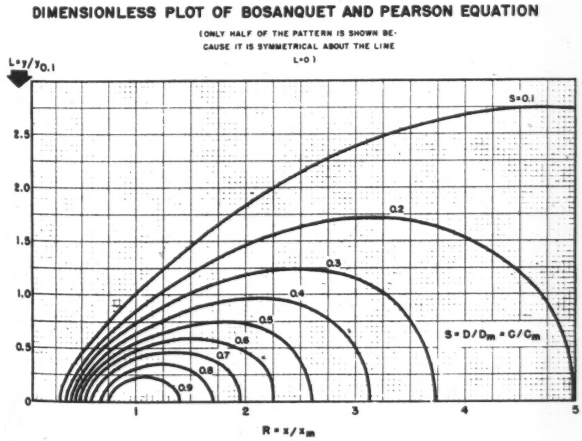

Fig. 13. Dimensionless Plot of Bosanquet and Pearson Equation.

A dimensionless plot was made of the downwind dosages observed for each field test with data sufficiently complete to determine with reasonable accuracy the values of x_m and $D_m = C_{mt}$, where D_m is the maximum dosage downwind and t is the time of pigment dispension. Similarly, the lateral (crosswind) distance fram the axis to the points where $S = 0.1$ was plotted in a dimensionless form. A curve of best fit was drawn for both crosswind and downwind plots and both curves are utilized to make the dimensionless area plot shown in Figure 14. Figure 14 is based on observed data plus the reasonable assumption of (a) a normal frequency distribution of concentration along the y axis at $x = x_m$, and (b) lines for $1 > S > = 0.1$ have the same relative shape as the line $S = 0.1$. Comparison of the observed area plot (Figure 14) with the theoretical plot (Figure 13) revealed significant differences in shape for values of R greater than 1.

1. The theoretical dosage becomes approximately twice the observed dosage as S approaches 0.1 ($R = 5$).
2. The differences in shapes can be interpreted as signifying that the horizontal diffusion coefficient, q, decreases with increased distance from the source while the vertical diffusion coefficient, p, increases with distance within the plume. The theoretical equation of Bosanquet and Pearson assumes p and q are constants for a given turbulence condition.

Use of the Dimensionless Plot

In order to describe the complete dispersion pattern of material emitted from a given stack, it is necessary to know three scale factors:

R = downwind scale factor
L = crosswind scale factor
S = magnitude scale factor

R and L define the actual shape of the dispersion pattern.

a. *Downwind Scale Factor, R*

Since $R = \frac{x}{x_m}$, it is first necessary to determine x. The ratio $\frac{\bar{u}}{\sigma_{us}}$ was found to be related to the distance x_m, in stack heights. This relationship is shown in Figure 15. Estimation of σ_{us} is somewhat difficult, however, from wind speed recording instruments when operated at a

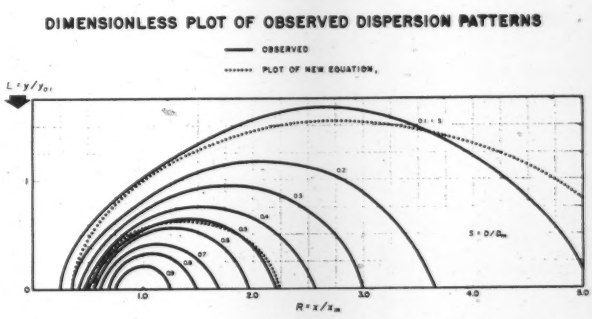

Fig. 14. Dimensionless Plot of Observed Dispersion Patterns.

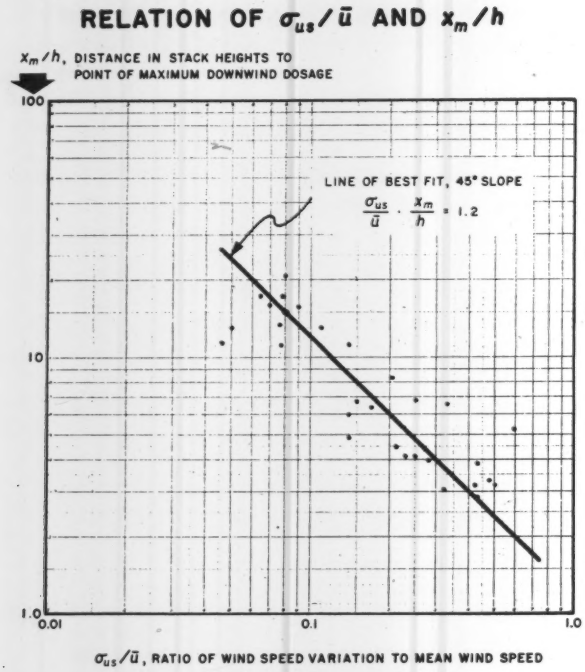

Fig. 15. Relation of $\frac{\sigma_{us}}{\bar{u}}$ *and* $\frac{x_m}{h}$

usual speed of 3 in./hour. At this recorder speed, the range of the wind speed variability, r_{us} i.e., the average width of the recorded wind speed trace, is relatively simple to determine for 10 minute time intervals. Examination of wind speed records for several field experiments showed that r_{us} during a 10 minute period was approximately $4\sigma_{us}$.

Thus the scale factor R can be determined from the range of the wind speed trace. Figure 16 is a working chart for the solution of the equation that relates wind speed variability to x_m. For example if $r_{us}\sqrt{u} = 0.7$ and h, the stack height, is 150 ft., the value of x_m is 1000 ft. Figure 16 can also be used to calculate the downwind distance from the stack to any value of $S = 0.1$ to 1.0. The values of S for $R < 1$ are given by the dotted lines, while those values of S for $R > 1$ are given by the solid lines.

b. *Crosswind Scale Factor, L*

The relationship between q, and σ_z can be used to calculate the crosswind scale factor, L. Just as in the case of wind speed, the range of the wind direction, r_z was found to be about 4 σ_z. It was found that $y_{0.1}$ in stack heights, was related to both r_{us} and r_z as follows:

$$\frac{y_{0.1}}{h} = \frac{12.8 + r_z}{25.3\,\frac{r_{us}}{\bar{u}}}$$

$$z = \theta S$$

From equation (8) and Figure 14, Figure 17 was prepared to permit graphic determination of the crosswind shape of the dispersion pattern at $R = 1.0$. For example,

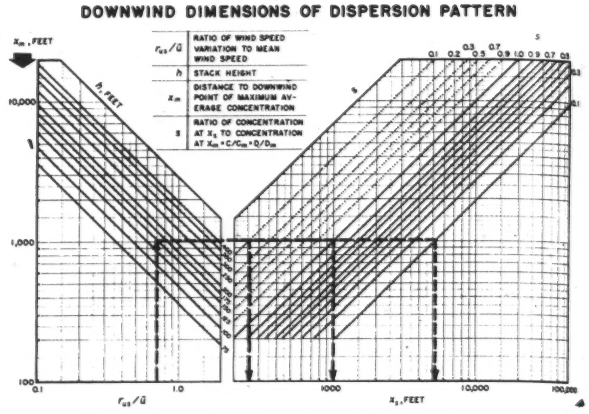

Fig. 16. Downwind Dimension of Dispersion Pattern.

if $r_{us}\sqrt{u} = 0.7$, $r_z = 10°$ and h *is* 150 ft., enter Figure 17 at 0.7 to $r_z = 10°$, rise vertically to $h = 150$ ft., and across to the line $S = 0.1$. This yields a value of $y_{0.1} = 190$ ft.; i.e., the crosswind distance to $S = 0.1$ at the point, x_m, is 190 ft. on either side of the mean downwind direction. The crosswind distance to other values of S between 0.1 and 1.0 can also be determined from Figure 17.

Thus, from Figures 14, 16 and 17, contours defining the ground level shape and relative magnitude of the dispersion cloud from a source for any turbulence condition indicated by a wind trace can be calculated. All that is required are the wind trace readings r_{us}, $\bar{u}$, r_z, and stack height h.

c. *Magnitude Scale Factor, S*

The magnitude scale factor, $S = \frac{D}{D_m} = \frac{C}{C_m}$ depends on an evaluation of D_m or C_m, the value of the maximum ground level dosage or average concentration at the center line of the dispersion cloud ($x = x_m$, $y = 0$). In most field tests, the observed dosages were higher than would have been expected from solution of Bosanquet and Pearson's equation. The insertion of a constant in

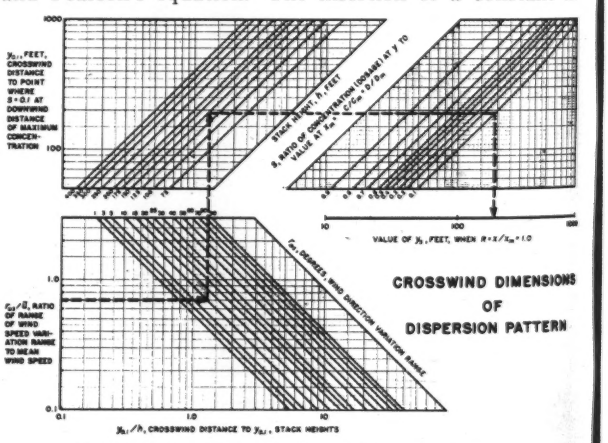
$y_{0.1}$, FEET, CROSSWIND DISTANCE TO POINT WHERE $S = 0.1$ AT DOWNWIND DISTANCE OF MAXIMUM CONCENTRATION
STACK HEIGHT, h, FEET
S, RATIO OF CONCENTRATION (DOSAGE) AT y TO VALUE AT x_m = C/C_m = D/D_m
VALUE OF $y_{0.1}$, FEET, WHEN $R = x/x_m = 1.0$
CROSSWIND DIMENSIONS OF DISPERSION PATTERN
$r_{us}/\bar{u}$, RATIO OF RANGE OF WIND SPEED VARIATION RANGE TO MEAN WIND SPEED
r_z, DEGREES, WIND DIRECTION VARIATION RANGE
$y_{0.1}/h$, CROSSWIND DISTANCE TO $y_{0.1}$, STACK HEIGHTS

Fig. 17. Crosswind Dimensions of Dispersion Pattern.

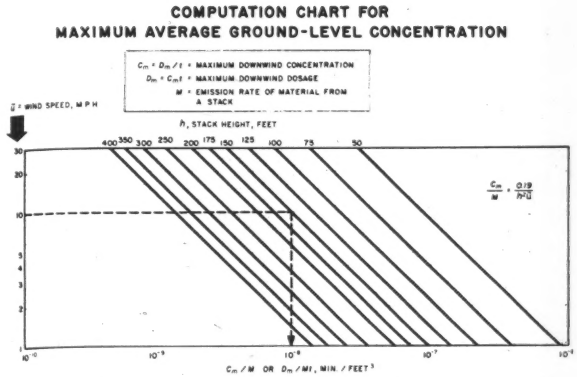
COMPUTATION CHART FOR
MAXIMUM AVERAGE GROUND-LEVEL CONCENTRATION
C_m = D_m/t = MAXIMUM DOWNWIND CONCENTRATION
D_m = $C_m t$ = MAXIMUM DOWNWIND DOSAGE
M = EMISSION RATE OF MATERIAL FROM A STACK
$\bar{u}$ = WIND SPEED, M.P.H.
h, STACK HEIGHT, FEET
400 350 300 250 200 175 150 125 100 75 50
30 20 10 5 4 3 2 1
$\frac{C_m}{M} = \frac{0.19}{h^2\bar{u}}$
10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6}
C_m/M OR D_m/Mt, MIN./FEET^3

Fig. 18. Computation Chart for Maximum Average Ground Level Concentration.

Bosanquet and Pearson's equation is a means of fitting the equation to the data. This constant, calculated for individual field experiments, could not be related, however, to the diffusion coefficients or to meteorological characteristics, such as wind speed or wind direction variability.

It was found that if D_m or C_m were computed from the following formula:

$$\frac{C_m}{M} = \frac{D_m}{Mt} = \frac{0.19}{h^2\bar{u}} \qquad (9)$$

the values of C_m would be within a factor of 2 of the observed concentration about 85% of the time and within a factor of 3 about 95% of the time. The value M is the emission rate of material from a stack.

Equation (9) is plotted in Figure 18. To use this chart, the mean wind speed and stack height must be known. For example, at a mean wind speed of 10 mph. and a stack height of 150 ft., the value of $\frac{C_m}{M}$ or $\frac{D_m}{Mt}$ is 9.6 x 10^{-9}. When the unit of M is in an appropriate unit per time, then C_m will have dimensions of those same units per volume of air. Table I gives some appropriate conversion factors to multiply $\frac{C_m}{M}$ to get C_m. Once C_m is determined, other values of C in the dispersion field can be determined since $S = \frac{C}{C_m}$

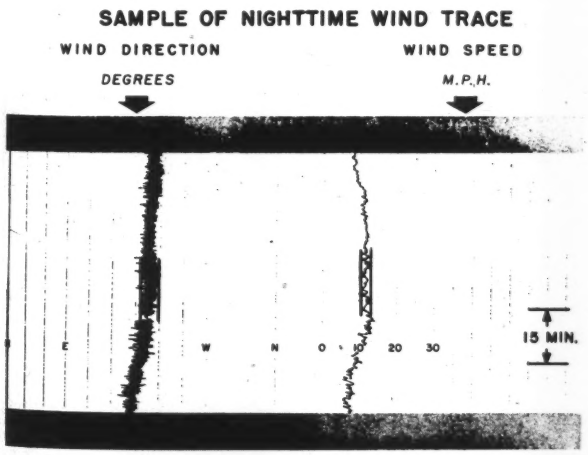

Fig. 19. Sample of Night-time Wind Trace.

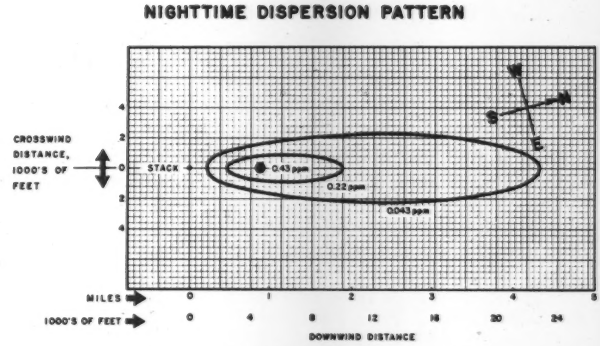

Fig. 20. Night-time Dispersion Pattern.

In both Figures 17 and 18, the equations based on measurements from a 100 ft. tower were extrapolated up to 400 ft.

d. *Sample Calculations*

Figure 19 shows the sample of a wind trace obtained about midnight. For the time period between the heavy parallel lines, the average wind speed, $\bar{u}$, is about 12 mph. The range of variability of wind speed, r_{us} is about 2.5 mhp. Thus $r_{us}\sqrt{u}$ is $\frac{2.5}{12} = 0.21$. The wind direction trace in Figure 19 shows r_z to be 23°. If, in addition, a 200 ft. stack emitting a material at the rate of 100 cfm. is assumed, then the shape and magnitude of the downwind dispersion pattern can be calculated from Figures 16, 17 and 18. Then with Figure 14 as a pattern, the complete dispersion pattern can be drawn for this stack (Figure 20).

Figure 21 is a sample of a daytime wind trace. In this case, the mean wind speed is 17 mph., the wind speed range is 13 mph. $\frac{r_{us}}{u} = 0.77$, and r_x is 85″. With same values of h and M as above, then the pattern shown in Figure 22 is obtained. Figure 22 and Figure 20 were plotted on the same scale for comparison.

Relation of Peak to Average Concentration

In the work discussed up to this point, the concentrations have been the average that would exist over a period of ¾ to 1 hour. It is known, however, that peak concentrations many times the average concentration occur in a dispersion field. Helmers[5] gave an illustrative example of this phenomenon.

Drum sampler data permitted calculation of the ratio of peak 1 minute concentrations to average concentrations during dispersion tests. These ratios, computed for those field experiments with adequate drum sampler data, are plotted against $r_{us}\sqrt{u}$ in Figure 23. Although the

CONVERSION FACTORS
TABLE I

If M Measured in	Multiply $\frac{C_m}{M}$ by	To Get C_m in
cu.ft./min. (cfm.)[1]	M	cu.ft. of M/cu.ft. of air
cfm.[1]	M x 10^6	parts per million (ppm.) by volume
cu.ft./ (cfh.)[1]	1.67 M x 10^4	ppm.
lb./min.	$\frac{3.59 \text{ M x } 10^{8*}}{w}$	ppm.[2]
lb./hr.	$\frac{6M \text{ x } 10^{6*}}{w}$	ppm.[2]
lb./min.	4.54 M x 10^5	mg./cu.ft.
lb./min.	1.60 M x 10^7	mg./cu.m.
lb./hr.	7.58 M x 10^3	mg./cu.ft.
lb./hr.	2.68 M x 10^5	mg./cu.m.
gm./min.	M x 10^3	mg./cu.ft.
gm./min.	3.53 M x 10^{-5}	mg./cu.m.
gm./min.	16.7 M	mg./cu.ft.
gm./min.	5.88 M x 10^2	mg./cu.m.
curies/min.	M	curies/cu.ft.
curies/min.	M x 10^6	microcuries/cu.ft.
curies/min.	3.53 M x 10^{-5}	curies/cu.m.[3]
curies/min.	35.3 M	microcuries/cu.m.[3]

*w = molecular weight of material of M emission rate.

1 At temperature and pressure of atmosphere.

2 At 0°C. (32°F.) and 760 mm. Hg. pressure. Multiply by T/273 and 760/p where T = absolute temperature of air (°K) and p = pressure in mm. Hg. to get ppm. at air temperature and pressure. If temperature is in F., use $\frac{\text{Temp} + 460.}{460}$

relationship is not clear cut, the curve gives an indication of how this ratio changes with the wind speed variability. Slight variations in the output of the pigment dispenser would appear as variations downwind and thus may contribute to errors in evaluating the relation of the peak-average ratios.

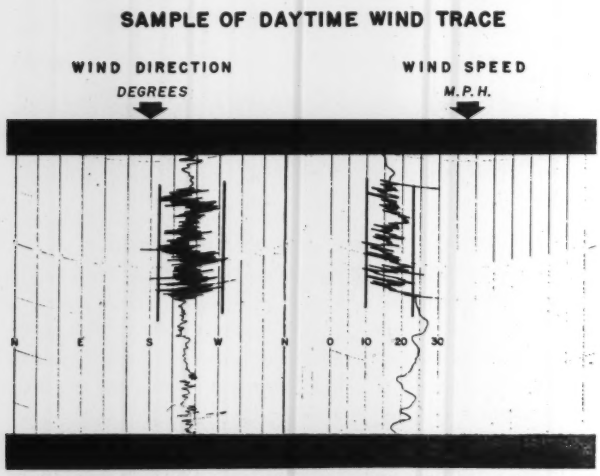

Fig. 21. Sample of Daytime Wind Trace.

5. Helmers, E. N., "The Meteorology of Air Pollution," Chapter 8, *Air Pollution Abatement Manual*, Manufacturing Chemists' Association, Washington, D. C. (1953).

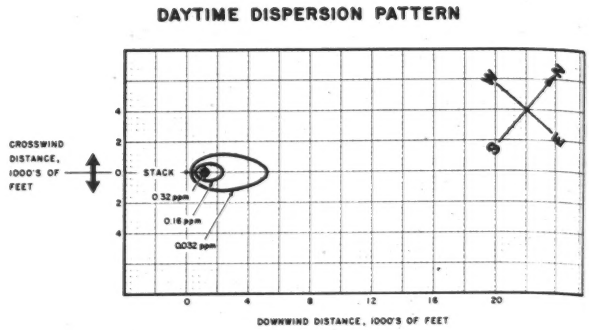

Fig. 22. Daytime Dispersion Pattern.

General Summary and Conclusions

The dispersion of atmospheric contaminants from an elevated source was experimentally measured using a direct tracer technique with fluorescent particles. Tests were made from an elevated source of about 100 ft. and the downwind dosage pattern was rather completely sampled. Variations of downwind concentrations with time were also measured. The results and conclusions can be summarized as follows:

1. The dimensions of the ground level dispersion pattern of stack effluents is related to simple measurements of wind speed and direction variation.
2. Standard wind recorders provide information that can be used to express completely the dispersion pattern. A simple and readily available tool is thus available for determining dispersion from stacks.
3. Working charts based on these wind measurements were developed for rapid calculation of the dimensions and magnitude of the average ground level concentrations. These calculated concentrations would be in most instances be accurate to within a factor of 2.
4. The ratio of wind speed variability to mean wind speed was related to the vertical diffusion coefficient.
5. The variability of wind direction was related to the horizontal diffusion coefficient.

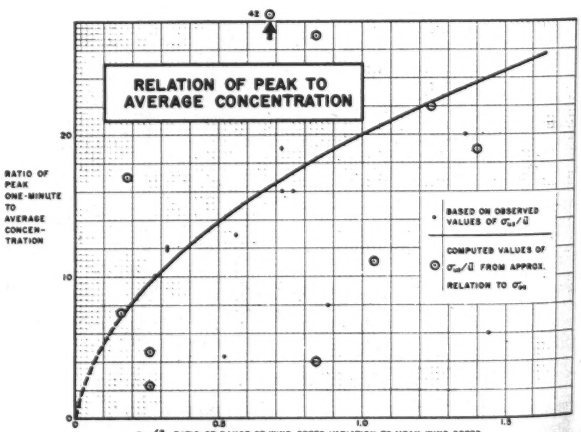
RELATION OF PEAK TO AVERAGE CONCENTRATION
RATIO OF PEAK ONE-MINUTE TO AVERAGE CONCENTRATION
BASED ON OBSERVED VALUES OF
COMPUTED VALUES OF FROM APPROX. RELATION TO

Fig. 23. Relation of Peak to Average Concentration.

6. The ratio of peak 1 minute to average ground level concentration is related to the wind variability.

Acknowledgments

The authors wish to express their appreciation to Dr. George S. Benton of The Johns Hopkins University for his many valuable contributions to this study. These included checking mathematical derivations, and deriving methods for computing dispersion coefficients. In addition, valuable information on the fluorescent particle technique or loans of certain equipment were obtained from the Chemical Department of Stanford University, U. S. Army Chemical Corps, U. S. Weather Bureau and the U. S. Navy.

DISCUSSION ON PAPER BY L. L. FALK et. al. ENTITLED "DEVELOPMENT OF A SYSTEM FOR PREDICTING DISPERSION FROM STACKS"

The authors have developed and applied a practical method for analyzing stack gas dispersion which should be of great value to investigators in the field. Presentation of results on a non-dimensional basis yields a simplicity of form which is time saving in its application and aids the understanding of procedures involved. It is hoped that this system will soon be applied to other situations to demonstrate its effectiveness and build up a body of information useful to the study of the more general aspects of atmospheric pollution.

Inspection of the wind speed and wind direction traces in Figures 19 and 21 suggests the possible existence of a correlation between their ranges of variability. The question arises as to whether a system for prediction of dispersion could be based on wind speed measurements only. Such a system would have the obvious advantage of eliminating the wind direction instrument but would suffer loss in generality through reduction in the number of parameters. Sutton, in the reference cited, gives a limited amount of data which shows the various diffusion parameters to be related and to have a single set of values for a given source height and turbulence situation.

G. H. STROM
New York University

The paper presents valuable new data on atmospheric diffusion of matter from a continuous point source, and a new technique of rapidly determining patterns of ground level concentration. A warm welcome to this contribution is tinged with regret that the authors did not have an opportunity to carry their investigations a bit farther in several directions.

It is usually desirable to start at the beginning, so a comment on the title of the paper may be appropriate. The title may lead the design engineer to believe that many of his problems of prediction have now been solved. However, much more is required than is obvious from a casual reading of the paper. For one thing, data on climatological conditions near a proposed plant site must be already available or must be measured. Data for one year is the minimum, and for five years is preferable. The climatic data obtained all over the country by the U. S. Weather Bureau do not include, unfortunately, observations of wind speed and direction fluctuations of the type described in the paper. Thus, a substantial program of specialized meteorological observations at a given proposed plant site is required.

Furthermore, the manner of emission of matter from the dispenser in the experimental program described differs in a number of respects from the way effluents are emitted from a stack. These are enumerated briefly below.

1. Stack gases are usually emitted with an appreciable exit velocity, which may sometimes be very high. Velocities as great as 120 fps. are becoming more prevalent. The emission is therefore of the jet type which induces its own turbulence and diffusion by mixing and which has received, when on a smaller scale, considerable aerodynamic analysis. The jet, in addition to inducing its own mixing, carries the gases to greater heights and thus increases the effective stack height.
2. When the stack gases are also hot, as they usually are, their buoyancy carries them even higher, so that the effective stack height is further increased.
3. With the higher winds that minimize the benefits of jet and buoyancy action, aerodynamic downwash of stack gases, of the type described by Sherlock and associates[3-4], may occur and carry the plume to lower levels.
4. When the stacks are on or near large plant buildings, which is often the case, the stack gases may be carried down into the turbulent wake which extends downwind from the building, also described by Sherlock and associates[3-4]. The rate of turbulent diffusion in such a wake, and hence the value of turbulence parameters, will practically always be greater than in the nearby undisturbed flow.

The results of all these influences, those of the jet, buoyancy, aerodynamic downwash, and building wake vary with meteorological conditions and will modify, often substantially, the conclusions reached in the investigation under discussion. The writer realizes that these other factors are well known to the authors of the paper, but since they have not been mentioned in the paper as received, he feels they should be outlined for the benefit of those who may not be conversant with all the complexities of the problem.

The writer believes that the next step is to make detailed studies near existing plants, introducing tracers into the stack gases if the latter do not contain natural tracers of a suitable type. In this way the four factors above could be studied simultaneously with the strictly meteorological aspects. In association with Professor Sherlock, the writer hopes to have an opportunity in the near

future to participate in such a comprehensive program of investigation.

With regard to the sampling techniques employed, the writer would like to ask if an attempt was made to evaluate the errors arising because the sampling was not isokinetic.

Wind speed, direction, and fluctuation measurements were made at a height of 108 ft. above ground. Since it will often be inconvenient to mount instruments at such a height near a proposed plant site, it might have been preferable to locate the instruments at a lower level, so that the conclusions could more readily be applied to other localities.

In the present investigation where the aim has obviously been to obtain design data, it would have been well to evaluate the diffusion coefficients not only from the conventional anemometer and wind vane records, but also from the records of instruments which have been specifically designed to measure turbulence. Examples are the gust accelerometer and the counting wind vane described by Hewson and Gill[2] and the counting bivane designed later by Thomas[5]. It was our experience in the Trail investigation[2] that when we developed apparatus that would measure turbulence directly and express it as a specific number (in our case—horizontal gust acceleration in miles per hour), plant personnel accepted measurements of turbulence as part of their program with a willingness and enthusiasm which had been notably lacking when they had been expected to evaluate a very irregular chart curve showing wind speed or direction fluctuations. Trained meteorologists, of course, have no reservations in interpreting such chart records, but other personnel do.

An important source of high concentrations at the surface is the fumigation condition described by Hewson[1]. In this, an accumulation of gas and smoke develops aloft in the early morning hours in the form of a ribbon of smoke extending downwind from the stack. After sunrise, solar heating causes a break up of this stable layer, in which high concentrations are brought to the surface to produce a fumigation lasting on the average about half an hour. No observations on this important cause of high surface concentrations are mentioned in the paper. Did the investigation cover this phase of the problem?

In the paper it is mentioned that vertical temperature gradient measurements were made by a wiresonde installation, but no analysis of lapse rate data is referred to. Did significant points bearing on the problem emerge from the analysis of these data?

An interesting and significant fact is brought out in the paper, when it is shown that fluctuations in horizontal wind speed are related to diffusion in the vertical. Such a result might have been expected on theoretical grounds, but the investigation clearly demonstrates the relationship.

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E. WENDELL HEWSON,
University of Michigan, Ann Arbor

(Continued from page 2)

Development of Incinerator For Drums

receptacle at the base of the water spray separator about once every two weeks. It is in a convenient form to handle and can be carted away. This handy way of disposing of soot from the process is certainly more satisfactory to the neighbors than when it was distributed over their property.

One of the early ills of this particular incinerator installation was the burning out of various parts of the metal conveyor system which were subjected to furnace heat. The steel chains propelling the drums and the rails of the conveying track failed because they could not withstand the temperatures encountered in normal operation. These faults were cured after some experiments with water-cooling the parts in question. The burning is now done with the drums moving through the furnace on a water-cooled electric motor driven conveyor.

The only other major operating problem which has developed is one of corrosion of recirculating water system pipes. This condition is probably the result of acidification of the spray water due to contact with sulfur laden furnace gases and residue. The problem has been temporarily solved by substituting rubber hose connections for iron pipe where necessary. It could very likely be solved by properly treating the water.

The incinerator will burn up to 150 to 200 drums per hour at a gas cost of about 1½c per drum and a total cost of 5c per drum with electricity and labor.

Drums are cleaned thoroughly and economically, and the neighbors have not lodged a complaint with our Division since the remodeled incinerator was put into operation. Soot and smoke are a thing of the past.

The most important point, lies in the fact that the misapplication of haphazard incineration has been corrected and not only was atmospheric cleanliness and good will realized but also a more reliable process with an advantage in dollars and cents.

Discussion of Papers in May Air Repair

DISCUSSION ON PAPER BY H. C. DOHRMANN, G. A. GALLAER, T. W. SCHINDELER ENTITLED "FACTORS IN THE DESIGN AND OPERATION OF INDUSTRIAL DUST COLLECTORS AS RELATED TO AIR POLLUTION"

It would appear that little confidence can be placed on reports of multiple independent screen analysis of similar dust samples made by methods commonly in use. Some dust collector manufacturers base their guarantees of efficiencies on the screen analyses of dust in the gas stream. Apparently, an improved method of analyzing sub-screen sizes of dust is needed.

It should not be overlooked that the plant owner has some responsibility. He should make sure that the equipment is operated and maintained in accordance with the manufacturer's recommendations. As long as the equipment producing the dust is operating, the collector should be kept in operation. I have known cases where collectors were turned off. This, like soot blowing, usually happens at night.

We must always keep in mind the importance of the human element. Men are sometimes careless, thoughtless or inattentive. This may result in improper operation or lack of regular maintenance. This emphasizes the importance of air pollution consciousness,—all the way down the line to the unskilled workman.

WILLIAM G. CHRISTY
Consulting Engineer, New York

DISCUSSIONS ON PAPER BY W. L. WILSON ENTITLED "AUTOMATIC IMPINGER FOR AIR SAMPLING"

The sampling instrument which Mr. Wilson has described includes features that adapt the unit well to the study of atmospheric pollution in relatively large areas by a small staff. In Oregon we have found that the conventional manually operated sampling units are inadequate to carry on a state-wide activity due to limits of personnel and facilities. Maximum use is being made of timing devices to regulate sampling programs. For instance, in order to reduce the variables due to changes in wind direction, the sampling area is used to allow sampling only within a pre-selected range of wind direction at the sampling station. We have used the automatic impinger in connection with area studies and it has been found to be a serviceable piece of equipment. The automatic features of the unit make the instrument particularly suitable for the study of air contaminants from intermittent sources. Also, the twenty-four hourly samples provide an effective check upon the concentration of air contaminant that varies widely within a short period of time.

It has been necessary to collect a considerable number of fluoride samples in connection with the study of areas adjacent to aluminum reduction plants. The approximately fifteen minute sampling time for each hourly sample is too short a period to collect a sample when the fluoride concentration needs to be known in tenths of a part per billion. In our regular sampling for fluoride concentration, using a standard impinger, a sampling time of not less than four hours at the rate of one cubic foot per minute has been used.

R. E. HATCHARD,
Chief, Air Pollution Control,
State of Oregon.

We have used the automatic impinger apparatus as described by Mr. William L. Wilson in the laboratory of the Bureau of Industrial Hygiene, Detroit Department of Health, for approximately 2 years. This inexpensive instrument has proven to be exceptionally dependable in respect to mechanical operation over a long period of continuous field use. Results of atmospheric sulfur dioxide measurements made with this instrument are comparable to those obtained from the Thomas Autometer within the limits of experimental error. Flow rates maintained by the instrument are satisfactorily uniform and calibration presents no particular difficulty. The volume of sampling or reagent liquid delivered to the impinger remains constant to with $\pm$ 5 percent. In our work, the usual sample period is 16 continuous minutes out of each hour. Under most circumstances of use, this operating cycle is satisfactory and neither over integrates the sample nor omits important information. We confirm Mr. Wilson's observation that the concentration of air pollution varies relatively slowly at locations reasonably removed from a local source of omission. We likewise find that under these circumstances, the location of the sampling point is not critical for either gases or fine particulate matter. Similar measurements are obtained even though the sampling point is located at street level, near buildings or several stories in the air. Needless to say, the duration of sampling time and location of sampling point becomes much more critical in the proximity of a significant local source and when the particle size of the dust is large. The development of a relatively simple, durable and inexpensive sampling unit of the type here described, is a valuable contribution to the study of air pollution. Although the advantages of automatic, continuous recording instruments are obvious, devices such as the automatic impinger have several favorable characteristics. A lower initial cost readily permits the purchase of a number of instruments to simultaneously sample several points during a survey of a problem in a critical area. The excellent portability, ease of maintenance and increased flexibility as to application must not be overlooked.

Treatment, presentation and interpretation of the voluminous data, which is derived from even a relatively single

air pollution study, poses perplexing problems. A machine method as proposed by Mr. Wilson, probably offers the best way of handling the large mass of complexing, inter-related data. All too often, the statistical aspects of air pollution study are not given sufficient consideration. A collection of a large mass of data in itself, is of little value. Not until the information is carefully collated and "decoded", can the investigator truly perceive the messages contained therein.

DR. W. G. FREDRICK
Dept. of Health, Detroit, Mich.

DISCUSSIONS OF W. C. HOLTON'S PAPER ENTITLED "ANOTHER LOOK AT REINJECTION OF FLY ASH FROM SPREADER STOKERS"

Holton's review of the only usable test data for collection performance from spreader stokers is disappointing in that only too few data are available from which air pollution control officials may judge the probable merits of boiler-collector combinations. Owing to the vagaries of purchasing agents, size consist of coal, plant operation and the public, the only sure way he has that a spreader-stoker fired plant will either meet his ordinance restrictions or likely fail to commit a nuisance is to require a collector of high efficiency (85% to 90%).

A plant which elects to not reinject fly ash and thus cut a capital investment corner by purchasing a low cost collector, may later change its mind and decide that the 3 to 5 percent in fuel value lost to the refuse dump is worth saving. Of course, plant size, operating conditions and annual fuel bill vary over wide limits and no rigid formula can cover all conditions. Each plant is largely a law unto itself with the exception that it must conform to the air pollution ordinance requirements and meet certain minimum engineering specifications as required in either the ordinance itself or its rules and regulations.

Since economics plays a major part in the selection of fly ash collection equipment, an example of probable difference in operating costs between high, medium and low efficiency collectors is interesting.

Assume the following:

Plant steam requirements, 2 boilers each	15000 lb/hr.
Annual coal requirements	6000 tons
Cost high eff. collector, ID fan, stub stack	$20,000.00
Depreciation, interest, repairs	2,500.00
Cost medium eff. collector, ID fan, stub stack	15,000.00
Depreciation, interest, repairs	1,875.00
Cost low eff. collector, steel stack 125'x6' dia.	15,000.00
Depreciation, interest, repairs	1,050.00
Percent savings, total reinjection	5.0
Percent savings, partial reinjection	3.0
Increased fuel cost per ton to permit low eff. collector	$ 0.30

As will be noted in the following table the delivered price per ton of coal dictates the economic desirability for total or partial reinjection while the efficiency of the collector dictates whether or not reinjection is possible without objectionable discharge from the stack.

PROBABLE ANNUAL OPERATING COSTS FOR SEVERAL COLLECTOR EFFICIENCIES

Collection Efficiency	Reinjection	Delivered price per ton $6.50	$7.50	$8.50
High eff. coll. +90%	Total reinjection	550.00	250.00	—50.00*
Med. eff. coll. 75%	Partial reinjection	705.00	525.00	345.00
Low eff. coll. 50%	No reinjection	2850.00	2850.00	2850.00

*Decrease in annual operating costs.

Kaiser, in a paper given before this association in 1951, showed that to meet the ASME dust limit, "when burning a coal containing 5 percent of minus 20 mesh particles a collector of 70 percent efficiency was satisfactory when the dust was not refired. A collector efficiency of 74 percent was indicated at partial refiring, whereas, a collector efficiency of 90 percent was required for total refiring of dust."

Simple cinder traps at the boiler outlet have been known to give satisfactory performance under favorable operating conditions and size consist of coal. But because these vary over wide limits between plants with little or no control on the part of the enforcement officials, they no longer are acceptable except in rare instances.

Testing of collector performance is costly and difficult which accounts for the lack of data which may be used to judge the probable acceptance of a particular arrangement. While considerable progress has been made in the design of collectors and preferred methods of reinjection, lack of comparative data between combinations of boiler configuration, reinjection arrangement and other considerations leaves the air pollution control official in an awkward position. The author makes a good case for "Another Look at Reinjection of Fly Ash from Spreader Stokers," but owing to lack of comparative data the control official must still rely on the collector manufacturer's reputation, the designing engineer's ability and his own "horse sense". If all three came up to par he is a first rate official; if there is a serious edficiency in any of the three factors—well!

E. D. BENTON
Ohio Coal Association

Reinjection of fly ash is doubtless economical in many cases and results in a saving in fuel. What about the dust concentration in the stack emission? With reinjection, the load on the dust collector is increased. It would appear that the dust concentration leaving the furnace is heavier. With the same amount and kind of fuel being burned, the quantity of fly ash in the duct or stack, beyond the dust collector is greater than if reinjection is not used. It seems to follow that the dust concentration at the stack outlet will be larger.

WILLIAM G. CHRISTY
Consulting Engineer

The whole problem of reinjection of fly ash boils down to the prevention of the re-entrainment of the ash in the

gases and the burning out of the carbon. Spreading by gravity the returned fly ash on the end of a traveling grate as it enters the furnace is a method that ordinarily should give good improvement over blowing the fly ash up into the furnace, particularly from the standpoint of recirculation of dust.

In the attempt to get the fly ash into the fuel bed, possible bad effects on the fuel bed must be watched. Sometimes it is like trying to burn an extremely low grade fine fuel. In one of our Federal plants, attempt was made to reinject fly ash through a nozzle over the top of the rear end of a large underfeed stoker. The ash that dropped into the bed completely disrupted the fuel bed lanes and caused ash difficulties so great that the scheme had to be abandoned.

Other possibilities of burning fly ash have been given study and should be given more study. One suggestion for large jobs was to burn it in auxiliary equipment. In any event, more development work, including better application of what is now known, appears to be in order.

Mr. Holton's paper is a valuable summary and discussion on present knowledge of reinjection.

J. F. BARKLEY
U.S. Bureau of Mines

Mr. Holton's paper is a fine contribution to the subject of Air Pollution. In his usual thorough fashion he has dug into the subject and come up with comparative results. His comparison of pneumatic reinjection with gravity return of the fly ash to the stoker is very interesting. Except for one illustration all of the information on pneumatic reinjection is of a single design. It is presumed that this was intentional in order to show the ineffectiveness of this application.

Certainly the simplicity of the pneumatic reinjection is desirable. Furthermore, this system can be applied to a great many different styles of boilers on which the gravity return would be a problem. The gravity return is readily adaptable to certain types of design but is practically impossible on certain boiler designs and in certain arrangements of dust collectors, air heater hoppers and boiler hoppers. There are no such limitations on the application of pneumatic reinjection. Mr. Holton inferred that the gravity return is the only method of reinjection that will meet code requirements and ignores the fact that many units are operating with total reinjection of pneumatic type doing a very creditable job. Mr. Holton's discussion of the A.S.M.E. Paper No. 52-A-142, "Furnace Heat Absorption In A Spreader Stoker-Fired Steam Generator" which appeared in the July, 1953 Issue of A.S.M.E. Transactions, commented upon the relative effectiveness of a pneumatic reinjection system as compared to a gravity system as follows:

"It is quite interesting to note that the curve in Fig. 4 for the dust loading at 14.5 percent CO_2 is in good agreement with the results of previous tests at Racine, Wis., as reported by Morrow, Holton and Wagner in 1951. The comparison is shown in Table 6 herewith.

TABLE 6—COMPARISON OF DUST LOADING BETWEEN WHITING AND RACINE TESTS

Racine test no.	Burning Rate K Btu per (sq. ft) (hr)	CO_2 per cent	Stack dust loading, gr. per cu. ft. std. conditions	
			Racine	Whiting
3	595	14.8	0.087	0.085
4	619	14.4	0.069	0.092
6	591	14.5	0.080	0.082

Test Nos. 3 and 4 in Table 6 were run using a washed 2-in x 0-in coal from the Island Creek seam and test No. 6 was run with washed screenings from the Illinois No. 6 seam. The agreement note in the dust loadings is "exceptionally good".

There have been many additional tests which confirm the information which appeared in A.S.M.E. Paper No. 52-A-142 concerning the low stack dust loading when operating with total reinjection with pneumatic systems. Developments and improvements in pneumatic reinjection systems since the Furnace Performance Factors Tests of the Spreader Stokers were run have resulted in a still better performance with respect to dust loading and stack emission.

Again we thank Mr. Holton for his fine contribution and for the very great effort that he has put into it.

E. C. MILLER
Riley Stoker Corp.

DISCUSSIONS ON PAPER BY A. R. STOCK ENTITLED "COAL SEGREGATION AS A CAUSE OF SMOKE AND ITS CORRECTION"

Mr. Stock has illustrated and discussed the segregation of coal and its effect on fuel bed very effectively. This is one of the problems encountered by all fuel service engineers and is very difficult to overcome unless some changes as suggested by Mr. Stock are made.

At the present time this problem is recognized by coal producers and sales companies and a number of methods are employed to load coal into railroad cars to avoid segregation in load. Where the mines are equipped with blending bins which receive coal from the cleaning and screening plant, normally three sizes, i.e., 1¼ x ¾, ¾ x ¼, ¼ x 0, are fed onto the conveyor belt in predetermined proportions to make up their standard 1¼ Nut and Slack. The proportions can be controlled accurately to provide any percent of consist. The loading boom is lowered into the railroad car to minimize segregation as loaded and an inspection of cars of coal thus loaded show an equal distribution of sizes.

Likewise mines that are not equipped with blending bins employ layer loading of railroad cars. The railroad cars are moved along the track under the loading boom and as many as five passes are made before the car is fully loaded. Often as many as five railroad cars are loaded in a group to insure a more uniform product in each car. This is quite important where more than one method of underground mining is being employed.

Also some mines even control the number of cars moving from various sections of the mines to the tipple or cleaning plant in order to provide a more uniform consist of coal from the particular mine.

Mr. Stock is correct in that all this blending and layer loading does not insure a uniform consist to the stoker hopper. More consideration should be given in the installation of coal handling equipment to prevent segregation.

Slides 22 - 23 - 24 - 25 illustrate the problem whether the coal is traveling down a chute or rolling off the apex of a pile. The slides shown of silos are about as found in general practice and in my opinion a conical or pyramid shaped distributor under the discharge of the bucket elevator will improve the distribution of sizes. A change in the shape of the gate where a bucket conveyor drops coal on a scraper conveyor will often overcome segregation. Also gate openings in scraper conveyors should be across the full width of the conveyor and not on one side.

Smoke from coal segregation is a self evident fact and it is much simpler to correct the cause of segregation than to try and overcome the smoke with changes in coal and air adjustment.

While it is important to have adequate coal handling equipment in any plant design, it is necessary, as stated by Mr. Stock, to check the plant design and avoid costly alterations after construction is completed. As members of the Air Pollution Control Association, you have an excellent opportunity to give assistance to plants with faulty coal handling equipment in overcoming their smoke and air pollution problems. This is a place where we all can help.

Thank you.

MINOTT BROOKE
C. & O. Railroad

This is a good paper in that it directs attention to the design of certain components of all coal handling systems to which no consideration has been, or is being given, for eliminating or even minimizing segregation of coal sizes.

It is also valuable in its analysis of the causes of size segregation in chutes and coal feed hoppers, and in its description of the effect on distribution of the various sizes to the fuel supporting areas of the stokers.

The size segregation illustrations used to explain the figures conform to conditions that I encountered over a number of years.

Conical chutes and several types of hopper distributors, where used, have largely eliminated size segregation in wide stoker hoppers. However, practically all chutes and hoppers receive their supply from a bunker, silo, or bin, where extreme size segretion usually exists and it is the distribution to these storage units that I believe require attention.

Silos are notorious for size segregation and failure of coal to move freely. In one case a 100 ft high silo having all 'live' storage, with the coal being drawn from the bottom to supply two spreader stokers, had its inlet chute entering through the wall, being cut off flush with the inside of the wall. This resulted in a condition as described in the paper with reference to Figure 9 under which all of the fine coal was deposited directly under the chute along the wall and the coarse coal was thrown to the far side away from the chute.

This distribution gave them a great deal of trouble. For one thing, the fine coal built up faster than the coarse coal so that before the level of the coarse coal was high enough to pass additional coal to the overflow chute, leading to outside storage, the fine coal reached the chute level to choke off the flow, producing a load against the conveyor of such degree as to throw out the overload switch; and this required that a man climb and enter the silo to release the load by moving the coal. It also resulted in varying sizes going to the stokers.

I recommended that the chute be extended to the center of the silo and that a spider of three chutes be added to it, that a definite level be maintained; and, as an alternative, installation of a Jacob's Ladder.

Notwithstanding the fact that the stoker manufacturer's operator was still running the units and also criticizing the sizing of the coal reaching the stokers, I did not succeed in having anything done toward correction, even though my proposals included methods and estimated costs.

It is interesting to note that the bunker design for some of the new installations has a single section for each boiler with a length conforming to that of the width of the boiler; and installations which I have seen, have a tripper belt with distribution through chutes on each side of the belt, making it possible to load the coal with little size segregation effect. By withdrawal through a number of chutes conforming to the number of stoker units, freedom from size segregation is carried to the stoker hoppers.

Ore bedding experience shows that by increase of the number of outlets, the material can be brought down in a mass without disturbing the surface. It also shows that bins having three equal dimensions offer the most likely design to keep uniform distribution to the chutes. Other requirements are that the chutes remain open so that the feed to each chute will be continuous; and along with this, more frequent supply of coal to the bunker or bin.

It is believed that the author's meaning is not as given in the first sentence with its implication that bad fires are caused by size segregation, for it is true that size segregation can be a cause for a bad fire, but it certainly is not the cause of all bad stoker fires nor is it believed that it enters as a factor into more than a small minority of such fires.

I have encountered many occasions when size segregation adversely effected the operation of hand-fires and stokers; and, on occasion, undertook considerable amount of sampling and analyses to determine the size distribu-

tion in various locations of the coal-handling system: chutes, conveyors, bunkers, and stoker-hoppers for the purpose of bringing out the need for correction in order to improve the distribution to the stokers, or to improve the free-movement of coal with a better mixture of sizes. In so far as I know, most of the larger industrial or utility plants did not consider the effect of such size segregation on the operation to be serious enough to justify any particular attempt to reduce the size separation, nor can I offer any evidence that improvement in efficiency or in maintenance would accrue by more uniform mixture of sizes going to modern units.

Some years ago, on individual applications to hand fired grates, single retort underfeed stokers, and short multiple retort underfeed stokers having tuyeres designed with a relatively few large area openings, positive improvement was obtained with reduction in size segregation. With modern designs and sensitive combustion control systems, it is believed that, with the ordinary range of the degree of size segregation and the time period involved in the size changes, correction is made by the controls at least to the extent where reasonable satisfactory conditions are maintained.

Actually, in the paper little evidence is given to substantiate that size segregation is a frequent cause for smoke. The single example, Figures 1 and 2, for a chain grate condition is not too convincing. While the smoke is shown to be heavy from the two piles described as segregated fines in Figure 1, the level bed of Figure 2 appears to be producing rather heavy smoke over the entire width of the grate. I might point out that the figures as shown in the paper do not bring out the evolution of smoke as clearly as it is brought out in the photographic plates.

I have not had too much experience with chain grate stoker operation but by design it would appear as though that type of stoker would be more sensitive to the effects of segregation than would others because of the fact that when the coal reaches the grate, it is not disturbed until the residue passes over the end to the ash pit.

I do want to point out, however, that I have reviewed the former National Electric Light Association's Prime Movers Committee Reports on Stokers and Furnaces for a period of several years starting with 1924, and did not turn up a single chain grate case where smoke or poor combustion was related to stratification of sizes when using Mid-Western coals.

One example reported by Commonwealth Edison referring to a new, at that time, forced draft installation having Babcock & Wilson Chain Grates showed that a furnace survey indicated that gas stratification and oxygen deficiency existed where the most rapid gas distillation was in effect, and that under no conditions could enough air be forced through the 6 inch bed to make up the deficiency. This may possibly have been caused by segregation, but hardly likely because correction was made by relocating the waterback, lowering and redesigning the bridgewall to restrict air admission to the rear, and at the same time direct it forward. This resulted in a reduction of excess air and carbon monoxide and shortened the flame length to confine it within the furnace.

In its 1927 Report, Milwaukee Electric Railway and Light reported they were prompted by the results obtained through the use of overfire air, as reported by Commonwealth Edison, to install overfire air through the front arches located in the multiple retort underfeed stoker fired furnaces at their Commerce Street Plant, for the purpose of eliminating smoke. This was reported as being entirely successful, needing no evidence other than could be observed through the plant periscope when opening and closing the overfire air dampers. They did, however, include a comparison of the average combustion gases with and without the overfire air: with no air, CO_2, 13.5%; CO, 1.2%; with air, CO_2, 14.3%; CO, 0.0%.

It must be borne in mind that these reports were made by member utilities who freely offered others their operating experience and procedures for overcoming difficulties or bad conditions, during the time when the utilities were entering the transformation period of steam generation equipment which has culminated in the present coal burning and steam generating design. No report indicated coal size segregation as a source of smoke.

The reference in the paper to spreader stokers as being affected by size segregation in a similar way to that given for chain grates does not appear to fit with the differences in the manner of coal admission for the two designs: for the one, coal is deposited on the grate in volume; while for the other, it is thrown from a level above the grate and is also spread which means that the spreader stoker is a good separator of sizes by design. This fact is accepted in the paper where it states that "It will be found that the fine coal will not be thrown as far as the coarse coal." But the paper also submits that smoke will result because the fine coal will pile up, reducing passage of air both by its resistance and through resulting clinker development.

This, in my view, is not necessarily true, nor is it generally encountered even with what can be considered extreme cases of size segregation. The main reason for this is, each unit feeder is an entirety that can be adjusted to meet the requirements of the sizes and condition of the coal in the hopper. Furthermore, the effect of size segregation is largely lost in the hoppers because they are relatively small and have almost equal dimension as referred to length and width, and the design of the rotors give criss-cross distribution with considerable penetration of coal from a given feeder to the grate section ahead of adjoining feeders.

Many cases could be cited; but as a point in this connection, I have recently spent a number of days at a paper mill plant having two, 3-unit spreader fired boilers

where segregation of sizes was known to effect the operation. The condition had been called to the attention of the engineer and management by the operators but nothing was done about it because the effect on operation was not considered to be serious.

This plant has a 1000-ton overhead bunker extending the length of the boiler room. The coal is unloaded to a track hopper and conveyed by bucket elevator to a screw conveyor which distributes it to the bunker through a number of openings in the bottom of the conveyor trough. These openings are all maintained wide open so that the coal is first supplied to the section below the first opening until the depth of coal closes it off, and the coal then passes to the next opening. In the writer's experience, this results, in extreme segregation of sizes so that if the bunker sections are maintained full, only small sizes are available at the outlet; but if allowed to run low, course sizes will largely flow to the chutes.

This plant system has a capacity of about 15 tons of coal per hour and the pile built up slowly as withdrawals were being made for both units so that over an extended period the rough sizes comprised the greatest percentage of the coal going to one unit with only fines being available for the other.

Under these conditions, two of the operating shifts made no manual adjustments depending entirely on the automatic control. The stoker receiving the coarser coal had heavy pile ups within three feet of the front end, whereas the bed was level on the stoker receiving the small sizes although at times there were also pile ups in similar locations to those generally found on the other.

This plant had been subjected to much complaint because of neighborhood cinder deposits and the management and operators were extremely sensitive to their chimney emission. The boiler gases discharged through a single, high, brick chimney which had a smoke indicator installed in each boiler flue, beyond a cinder collector and then boiler induced draft fan. A continuous chart record of the gas density passing the indicators was available for observation by the operators.

This record, regardless of the fuel bed conditions, as referred to variable depth and pile ups with underlying clinker, level thin fires, with or without underlying clinker, for a four-hour operating period between cleanings, showed densities of not over 10 per cent and more often between 0 and 5 per cent with the indications being about the same for each unit.

However, at the start of each cleaning, for each stoker, the density would rise precipitately to close to 100 per cent then drop rapidly to a position ranging from 20 to 50 per cent where it ranged throughout the balance of the cleaning operation.

The maximum reading resulted from a large manually made increase in coal feed rate for two of the three units to compensate for the loss of output from the unit being prepared for dumping and undoubtedly was a result of smoke, in part, and of fine coal solids.

Conditions of neither fuel bed had any effect on smoke production, but the unit receiving the smaller size coal gave somewhat higher capacity and slightly higher efficiency.

Other examples, which will not be discussed, include applications of various sizes of coal to a 150,000 lb per hr boiler having a turbulent type furnace where the spreader units are located 14 ft above the grate; 2 — 150,000 lb per hr spreader fired units in an outdoor plant with operation from a control room and hourly personal checks at the boiler.

Bad conditions involving segregation and poor fires were common to both installations. Emission of solids was a problem for each. Neither produced smoke.

F. J. KASPER
Eastern Gas and Fuel Associates

DISCUSSION OF PAPER BY C. H. BARNARD ENTITLED "INCREASED EFFICIENCY AND DECREASED SMOKE WITH BOILER INSTRUMENTS AND CONTROLS"

Not enough technical material has been published on the instrumentation of small and medium size boiler plants. Mr. Barnard's paper, therefore, represents a very useful contribution in this field.

The author rightly stresses that smoke is not an isolated phenomenon to be solved away from boiler operation and design, but that in many cases it is a symptom of inefficient operation. Provided furnace and stoker design are adequate for the given load conditions, automatic control provides an invaluable aid for maintaining high combustion efficiencies throughout the operating cycle.

However, is it the author's implication that the use of controls results automatically in the elimination of smoke? Does he include in this system overfire air controlled by automatic smoke control? It is hoped that the author will not mind a few supplementary remarks in order to clarify some of these thoughts.

As a first step, it is necessary to distinguish between automatic combustion control and automatic smoke control. It is possible to have either one without the other or both together in a plant. Having made this distinction, the question resolves itself into: "Is automatic combustion control sufficient to eliminate smoke at the source and thereby does it eliminate the need for additional automatic smoke control?"

Of the four fundamental combustion methods: pulverized fuel, underfeed, crossfeed, and overfeed, the first two are essentially smokeless. Assuming good furnace design, automatic combustion control helps maintain good stoker operation and thereby eliminates smoke during normal running. However, smoke may still occur at certain times due to cleaning of fires, manipulation of the fire bed by the operators, changes in fuel sizing, etc. For these occa-

sions, automatic smoke control, operating overfire jets may indeed be useful and justified, but the final decision will depend upon the size of the plant. A conscientious fireman by careful manipulation and judicious use of overfire jets may, as we all know, keep smoke emission within acceptable limits.

A special case is the emission of smoke from a single-retort underfeed stoker, using a simple on-off control. Immediately after the stoker fan stops, a simple time-relay which allows the overfire jet fan to run another few minutes without the stoker could insure burning of all the volatiles without smoke.

The spreader stoker is in a class by itself. The green fuel is introduced into the furnace in an atmosphere low in oxygen. As the volatiles distill off, some of the heavy hydrocarbons crack and form smoke. In contrast to the underfeed stoker, the spreader stoker requires overfire turbulence during normal operation. An overfire jet system may therefore be regarded as an essential part of a spreader-stoker installation. The overfire air fan may be linked to the main combustion control which governs the primary air fan, increasing and decreasing overfire air in the same proportion as the primary air. A spreader stoker therefore does not require a separate smoke controller. While not necessary, a smoke recorder or indicator is helpful in watching boiler performance.

The emission of smoke during low-load operations of a spreader-stoker is a problem which cannot be solved by automatic combustion control or smoke control with overfire jets. Only very careful stoker and furnace design can eliminate this problem.

The small plant is especially sensitive to initial cost as well as maintenance cost. It is therefore important to keep instrumentation and controls simple and robust—and preferably few in number. Mr. Barnard's paper represents a useful contribution towards reaching this end.

CHARLES H. MARKS
Bituminous Coal Research

Mr. Barnard's paper is certainly a valuable paper to be presented before the Air Pollution Control Assn. It does an admirable job of bringing together many of the instrument and control advances that have taken place in the combustion process. In fact, it goes further and serves as a demonstration of what modern day controls can do in terms of higher equipment efficiencies and reduced atmospheric pollution.

The ideal boiler room condition from a meter and control standpoint such as that found in the Bailey Meter Company's home plant is, at this time, far from typical; it is closer to a dream condition. The chances of making this dream condition become a reality depend very largely on the cost advantages such controls would offer. Where fuel savings or reduced labor charges can be demonstrated, the equipment has a good chance of going in. However, unless or until savings measure large enough to convince plant management that money saved is as good as or better than the return from an equal investment elsewhere in their business, the chances fade.

The most realistic advance in air pollution control thinking as far as easing the chances of getting better controls or more efficient auxiliaries, is that represented by the Capehart Bill. This request for legislative action advanced in Washington, D.C. in conjunction with a housing bill spells out a suggested rapid amorization for equipment that would help control or reduce atmospheric pollution. We know many members of this Association have long favored such legislation and several enforcement officials actively plugged for the Bill's passage. This same or very similar sentiment is expressed in other bills such as the Kuchel measure before the U.S. Senate, and in legislation before many of the individual state assemblies.

We feel these bills will go through eventually. When they do, information such as the curves Mr. Barnard gives in his paper will prove the value of better meters and better controls towards a higher degree of air pollution regulation.

JOSEPH C. McCABE, Editor
COMBUSTION

Mr. Barnard has done a very good job on a very timely and important subject. There are too many coal-burning plants hobbling along with a bailing-wire set up, violating smoke ordinances and wasting their own money. The net result is a black eye for coal.

The combustion of fuels has gone through several stages and coal has had the longest and most changing history. It began with crude, unscientific hand-firing, passed through improvements in hand-firing, through simple stoker-firing and today is entering the age of automatically controlled stoker-firing. Being relatively new, we still have much to learn concerning application, operation and maintenance.

We must recognize that while the human mind and body are a wonderful team, there are also human failings or shortcomings. We must also admit that even the best instruments and controls are dependent on the human element for correct and efficient operation. They must be checked, calibrated and maintained to be able to do a good job.

I believe the answer is more fireman education, supplemented by adequate instruments and controls. In fact, a fireman who really knows his "stuff" realizes the necessity of such devices and needs only a few tips on how to best use them. The real problem is in selling management on the idea of spending money. It is a horrifying fact that money will be spent in every place but the boiler

room. But most good executives are interested in saving money even though they might not be enthused about making the fireman's job easier. So, to sell equipment, we must save money for management and make life easier for the fireman—then everyone is happy.

This Association and many air pollution control officials have done a good job in showing that air pollution is too often a result of wasted money, especially where smoke is concerned. Investments in smoke corrections saves money.

No fireman should be expected to efficiently operate a boiler plant without draft and pressure indicators and a steam flow indicator/integrator. Other instruments that come very close to being a necessity are the CO_2 or O_2 recorder and a flue gas temperature recorder. If these instruments are to be intelligently used, the firemen must understand their function and operation. Too often a CO_2 meter is far off calibration, or even inoperative, because no one knows how to clean and calibrate it. A good fireman can tell the conditions within his boiler by noting draft and temperature records. These devices are not only tools for the fireman, but serve as excellent means for management to check the operation of the plant. We encourage a plant to measure coal consumption, either by a scale, or in smaller plants by using a known bucket to fill the hopper. This information used with the steam produced tells the cost per thousand pounds of steam. In such a way a plant can select the coal yielding the lowest cost. This often is not the coal with the lowest cost per delivered Btu. Of course, to be exact, labor, maintenance, overhead, depreciation and ash handling must be included in the calculation; but usually the steam produced—coal used figures tell a pretty comparative story.

It is a good practice today to install a smoke recorder in any coal-fired plant. Smoke records are invaluable in checking firing procedures, boiler-stoker operation, and are evidence in the case of reported smoke violations. A fireman can't deny such a record; and knowing this, he will make more of an effort to maintain good conditions. While manual control of overfire jets can eliminate periodic smoke nuisance, it is far better to eliminate human failure by installation of a control device to actuate the jets. It should be remembered and emphasized that this device is worthless if not calibrated, located and operated correctly.

On many jobs complete combustion control systems are economically justified on others only certain parts of the system such as a draft control will be needed. Load and local conditions determine the final setup.

It is also a fact that proper control application not only reduces operating costs but often lowers maintenance costs as well. Many mechanical failures in stoker and boiler can be traced back to poor operation. A good control is actually a fireman, properly supervised, on the job 100% of the time.

Often corrosion and erosion can be reduced by proper modulation of a stoker; hot, then cool stacks may aggravate condensation and the associated troubles while lower, more uniform rates of operation produce less tube cutting caused by high gas velocities. Modulation also reduces fly ash in smaller jobs when replacing on-off operation. Smoke in underfeeds is also reduced since it occurs mainly for a few minutes at the start of each off period. One of the things most needed is "over-compensation" so that on widely varying loads, steam pressure does not drop too far or override to where the limit control shuts the stoker off. This would mean utilizing "trends" in operation of the controls. A lot of smoke is produced in underfeeds when a stoker has been pushed hard and then suddenly is stopped by limit control operation. Automatic controls, properly set, should relieve the fireman of much of his work, but none of his responsibility; so he must know how to readjust the controls if the situation calls for it. Some controls do not maintain a uniform air/fuel ratio over a wide enough range. Linear movement of a damper swinging on a pivot does not give linear changes in volume of gas or air passing through the duct or opening.

Draft controls are used to reduce excessive draft—they can't possibly create more draft. It is true that automatic controls tend to iron out extreme rates and thus reduce maximum draft requirements, but plenty of draft must be available if the control is to do its job. Also, they must be set so that at maximum load, adequate draft is available. I have seen some jobs where the draft was throttled back to the correct level at lower loads but the linkage did not allow full opening of the damper to handle maximum load. This is no fault of the control, but rather points to poor utilization and adjustment.

In summing up, I feel that we must do a selling job, but we must be careful not to oversell as well as not to undersell. It may seem like good business to load up a plant with instruments and controls, but when we walk into a boiler room and find some of these just hanging on the wall and not in use it is apparent that someone has slipped. Few plants can afford thousand-dollar decorations in the boiler room. If a device is sold it must pay for itself and its operation and care should be thoroughly understood by the men who are going to use it—they must know what is expected of them if the control is to do its job, and they must know of what use to put the information presented by instruments if top notch operation is to be obtained. I have yet to see any system of controls that didn't need human supervision and checking.

We need more contributions like Mr. Barnard's and we need not only more instrumentation and control, but also better utilization of this equipment after it is installed.

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